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16. ABSTRACT

Research projects and investigations were reported which focused upon defining appropriate technologies for alleviating water quality problems from irrigated agriculture. The emphasis was on better water management practices. Case studies provided insights as to how these technologies might be implemented. Legal approache and socio-economic considerations that must be taken into account in arriving at alternatives for implementing programs of irrigation return flow quality management were presented. The major objectives of the conference were to (1) present the results of recent research pertinent to the subject; (2) integrate the research results into an interdisciplinary approach to solving the problems; and (3) provide a forum for presenting and discussing the alternatives in implementing irrigation return flow quality management and/or control.

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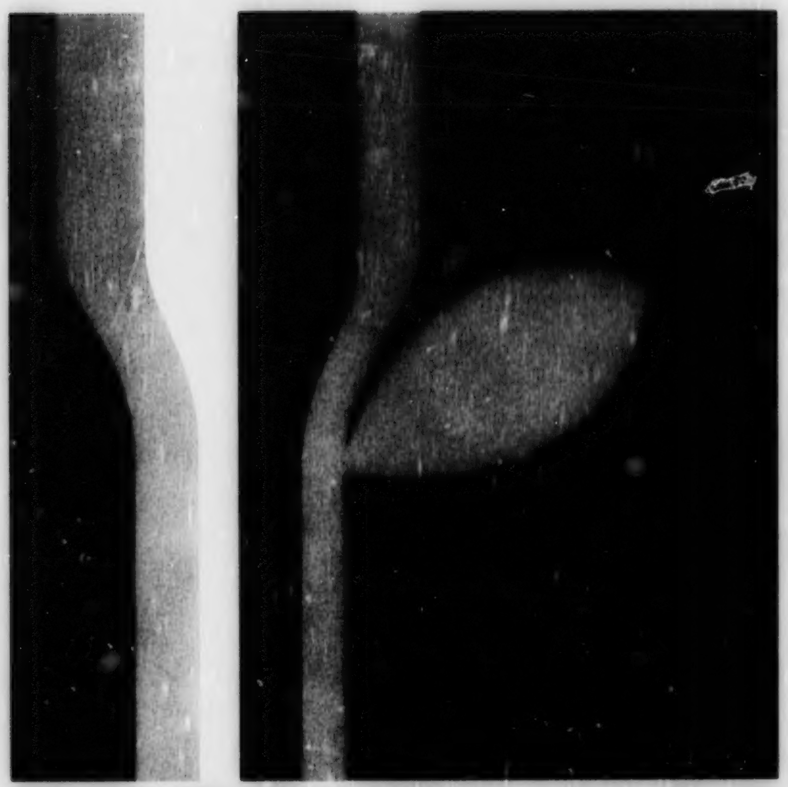

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PREFACE

Previously, the U.S. Environmental Protection Agency (EPA) and Colorado State University cooperatively hosted a National Conference on Managing Irrigated Agriculture to Improve Water Quality. This conference was held in Grand Junction, Colorado from May 16-18, 1972. A few years prior to this time, EPA had formulated its irrigation return flow research and development program. Then, a number of research grants had been initiated throughout the western states to launch this program. The conference in Grand Junction focused primarily upon: (1) identifying and describing irrigation return flow quality problems; and (2) describing the research being undertaken to develop solutions to problems of irrigation return flow quality.

The EPA irrigation return flow research and development program has made substantial progress in the past five or six years. Numerous research projects and investigations have been recently completed (or are nearing completion) which focused upon defining appropriate technologies for alleviating water quality problems from irrigated agriculture; most of these technologies involve improved water management practices. In addition, case studies have provided necessary experiences as to how such technologies might be implemented. These field experiences, combined with studies of legal approaches, as well as studies concerned with defining the processes of implementation and the socio-economic considerations that must be taken into account prior to and during implementation, have provided valuable insights as to the available alternatives for implementing programs of irrigation return flow quality management. Thus, holding this National Conference on Irrigation Return Flow Quality Management provides for the timely dissemination of the results from EPA's program.

The primary objectives for this conference to be held May 16-19, 1977 will be to: (1) present the results of the irrigation return flow research and development program of the U.S. Environmental Protection Agency; (2) integrate the research results into an interdisciplinary approach for solving problems of irrigation return flow quality management; and (3) provide a forum for presenting and discussing the alternatives in implementing irrigation return flow quality control.

We are now at that point in time where sufficient research and investigation has been completed so that more intelligent decisions can be made to solve the water quality problems of irrigated agriculture. These problems need to be addressed. From a national and local standpoint, now is the time for everyone concerned to provide their input — to weigh the alternatives and voice their opinions — in order that appropriate and viable programs will be implemented that are sensitive to both local and national needs and priorities.

The editors appreciate very much the cooperation of the authors in meeting the necessary time schedule for printing these proceedings so that they would be available at the time of the conference, May 16, 1977. We are deeply indebted to Stephen W. Smith and Richard L. Aust of the Department of Agricultural and Chemical Engineering, and Ms. Patricia Tietz of the Printing and Publications Office, all at Colorado State University, for their many hours of effort to insure that this proceedings would be available for the conference registrants.

James P. Law, Jr.
Gaylord V. Skogerboe
April, 1977

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PUBLISHED REPORTS FROM EPA'S RESEARCH PROGRAM ON IRRIGATION RETURN FLOW QUALITY ....

The Role of EPA's Office of Research and Development in Irrigated Crop Production Research

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ABSTRACT

In setting the stage for the conference, the role of the Irrigated Crop Production research program will be described. The legislative mandates of PL 92-500 to EPA will be reviewed in relation to the charge to control water quality degradation resulting from agricultural activities. The overall objectives of the program, established prior to the passage of PL 92-500, appear to be valid and supportive of the efforts of the program thus far. This conference represents a compendium of the results of the program's efforts as well as a hard look at the future direction the program should take.

Supported research has included technology development and evaluation of its effectiveness in water pollution abatement and/or control. The technology investigated has included both structural and nonstructural improvements within the water delivery, farm, and water removal subsystems of irrigated agriculture. Additional studies have investigated the legal, socio-economic, and/or other institutional constraints to water management reform. More effort will be required in these areas.

Current program emphasis is evolving into a phase which we are referring to as implementation research. Included in this is the preparation of research-based guidance documents aimed at providing much needed information for those state agencies responsible for planning and implementing areawide wastewater management alternatives involving nonpoint source agricultural activities. The discussions of this conference should provide great impetus toward that goal.

INTRODUCTION

On October 18, 1972, the 92nd Congress signed into law the "Federal Water Pollution Control Act Amendments of 1972". This act sets forth an ambitious goal to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters". In order to achieve this objective, Congress declared the following national goals and policies:

Section 101. (a)

"(1) It is the national goal that the discharge of pollutants into navigable waters be eliminated by 1985;

"(2) It is the national goal that wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983;

"(3) It is the national policy that the discharge of toxic pollutants in toxic amounts be prohibited;

"(4) It is the national policy that Federal financial assistance be provided to construct publicly owned waste treatment works;

"(5) It is the national policy that areawide waste treatment management planning processes be developed and implemented to assure adequate control of sources of pollutants in each state; and

> "(6) It is the national policy that a major research and demonstration effort be made to develop technology necessary to eliminate the discharge of pollutants into navigable waters, waters of the contiguous zone, and the oceans."

The above statements come from Public Law 92-500, 92nd Congress, S.2770, October 18, 1972, which documents the amendments to Section 2 of the Federal Water Pollution Control Act. The 1972 amendments replace the previous languages of the Act entirely including the Water Quality Act of 1965, the Clean Water Restoration Act of 1966, and the Water Quality Improvement Act of 1970, all of which have been amendments of the Federal Water Pollution Control Act first passed in 1948. Subsequently, P. L. 92-500 has been amended by P. L. 93-207, December 8, 1973; P. L. 93-243, January 2, 1974; P. L. 93-592, January 2, 1975; P. L. 94-238, March 23, 1976; and P. L. 94-558, October 19, 1976. These amendments have not substantially changed the intent of P. L. 92-500 but rather are meant to clarify the wording of various sections and subparts thereof.

The Congress addressed the responsibility of the Nation in achieving these goals and policies in Section 101 (b). There is is stated "It is the policy of the Congress to recognize, preserve, and protect the primary responsibilities and rights of States to prevent, reduce, and eliminate pollution, to plan the development and use (including restoration, preservation, and enhancement) of land and water resources, and to consult with the Administrator in the exercise of his authority under this Act. It is further the policy of the Congress to support and aid research relating to the prevention, reduction, and elimination of pollution, and to provide Federal technical services and financial aid to State and interstate agencies and municipalities in connection with the prevention, reduction, and elimination of pollution."

The Congress also addressed the administration of the Act in Section 101 (d): "Except as otherwise expressly provided in this Act, the Administrator of the Environmental Protection Agency (herein after in the Act called 'Administrator') shall administer this Act." Thus, we can see that the Environmental Protection Agency has the responsibility of administering the congressional intent of P. L. 92-500. The primary responsibilities of the Agency are spelled out in Title I — Research and Related Programs, Title II — Grants and Construction of Treatment Works, Title III — Standards and Enforcement, Title IV — Permits and Licenses, and Title V — General Provisions.

The intent of this paper is to provide some insight into the Agency's charge given by Congress and how research funded by the Agency fits into the overall operation of a regulatory Agency. The Agency was created by Presidential Reorganization Plan No. 3 in December 1970. This plan brought together 15 programs scattered among several Federal Government Agencies to mount a coordinated attack on environmental problems. These problems include air and water pollution, solid waste management, pesticides, water supply, radiation, noise, and toxic substances.

Organization and Functions of EPA

EPA must maintain and enhance environmental quality in a way that is consistent with other national goals. Functions performed by EPA include: setting and enforcing environmental standards; researching the causes, effects, and control of environmental problems; assisting states and local governments through a variety of planning and waste treatment facility construction grants; disseminating information on environmental problems and solutions; educating the public; demonstrations of how to protect and enhance the environment; and providing technical assistance in solution of environmental problems. To better understand this relationship it is appropriate to look at the manner in which EPA is organizationally structured and the relative role of the various key elements. This structure is given in Figure 1. The functions of the key elements and their interrelationships are briefly as follows:

Office of the Administrator. This office is responsible for the supervision and direction of the programs and activities of the Agency.

Office of the Assistant Administrator for Planning and Management. This office is responsible for the overall management activities of the Agency . . . coordinates planning, evaluation, and standard setting efforts . . . directs the Agency's resource processes . . . and provides administrative support.

Office of the Assistant Administrator for Enforcement. This office serves as the principal advisor to the administrator in matters pertaining to the enforcement of standards for environmental quality and is responsible for the conduct of enforcement activities on an Agency-wide basis.

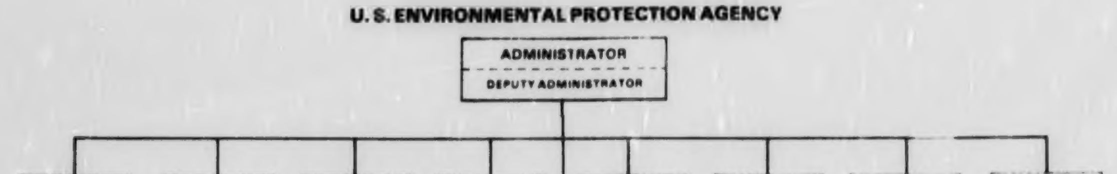
Office of the Assistant Administrator for Water and Hazardous Materials. This office is responsible for the Agency's pesticide, toxic substances, and water programs . . . develops standards, criteria, and national policy (except for the area of enforcement and research).

Office of the Assistant Administrator for Air and Waste Management. This office is responsible for administration and operations of the Agency's air, solid waste, noise, and radiation programs . . . policy evaluation assistance and selected demonstration projects.

Office of the Assistant Administrator for Research and Development. This office is responsible for the development, direction, and conduct of a national research, development, and demonstration program in pollution sources, fate, and health and welfare effects; pollution prevention and control, and waste management and utilization technology; environmental sciences; and monitoring systems. The AA for R&D serves as principal science advisor to the Administrator and coordinator for the Agency's policies and programs concerning carcinogenesis and related problems.

Regional Offices. The country is divided into ten regions, each region being administered through a regional office. The primary responsibility of the regional administrator in each region is to accomplish the national program objectives. The regional administrator and his staff serve as the Agency's principal representatives in that region in contacts and relationships with Federal, State, and local agencies; industry; academic institutions; and other public and private groups.

With this overview of the Agency structure and functions we can look more intensively at the role of the Office of Research and Development (ORD). In support of the Agency's mission, the ORD conducts a comprehensive and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OFFICE OF WATER PROGRAM OPERATIONS
OFFICE OF WATER SUPPLY
ASST ADMINISTRATOR FOR AIR AND WASTE MANAGEMENT
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OFFICE OF MOBILE SOURCE AIR POLLUTION CONTROL
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ASST ADMINISTRATOR FOR RESEARCH AND DEVELOPMENT
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Figure 1. Organizational Structure of the Environmental Protection Agency (June 1976).

integrated research and development program to provide:

- The scientific and technical base for reasonable standards and regulations.
- Standardized methods to measure and assure quality control in programs to assess environmental quality, implement regulations and enforce standards.
- Cost-effective pollution control technology and incentives for acceptance of environmentally sound options.
- Scientific, technical, socio-economic, and institutional methodologies needed to judge environmental management options against competing national needs.

ORD's research is supplemented by general scientific and technical research in other federal agencies, colleges and universities, and elsewhere. Governmental agencies function in a manner different than academia in that the scope of interest and objectives of endeavor are closely tied to legislative mandates and they must provide outputs applicable on a national scale. ORD establishes its objectives and priorities in response to the overall mission and priorities of EPA and is highly mission oriented, concerned with solving specific priority problems rather than only advancing scientific knowledge. Although the scope of ORD projects may vary from quite fundamental research to the full-scale engineering demonstration of new pollution control processes, all projects are directed at meeting specified objectives.

Within ORD, research related to the agricultural industry is handled administratively under the Office of Air, Land and Water Use (Figure 1) in the technical program area of Industrial Processes. The Industrial Processes Program Area contains the Renewable Resources Subprogram which includes Irrigated Crop Production, Non-Irrigated Crop Production, Forest Management, Animal Production, and Alternate Pest Management. The Renewable Resources Subprogram encompasses the development of total management systems, including predictive methodology to control air, water and land pollution from the production and harvesting of food and fiber and their related residual wastes; and assessment of probable trends in the productiion of renewable resources and their resulting environmental impact.

Problem Definition and Program Objectives

Irrigated Crop Production aspects of the Renewable Resources Subprogram are administered by the Irrigated Agriculture Section, Source Management Branch, Robert S. Kerr Environmental Research Laboratory, Ada Oklahoma. The control of environmental degradation caused by irrigated crop production is a multifaceted problem involving technical, legal, economic, and institutional considerations. The objective of this program is to develop and demonstrate the fundamental technology needed for full-scale pollution control programs in irrigated areas. This technology includes: canal and lateral lining and other structural controls for water delivery systems; methods to minimize water use and increase water use efficiency; control of nutrient losses; salinity control; sediment control; controlled leaching losses; pesticide transport in irrigated systems; and treatment processes. Evaluation of the legal, economic and institutional constraints to water management reform and technology changes is required. Development and verification of mathematical simulation and predictive techniques based on physical-chemical-biological processes occurring in irrigated soil systems is required to assess the effects of on-farm water management practices on the water quality of receiving streams. These models can be used to develop technically sound alternative pollution control management schemes for irrigated systems. The alternatives will include waste stream treatment processes. The output would be used by Federal, state, and local planning and pollution control agencies for the assessment and control of pollutants resulting from irrigated crop production activities. Water quality problems arising from irrigation activities are influenced by water, crop and land management practices and by the agricultural chemicals (fertilizers and pesticides) applied to the land. The major water pollutants from irrigated land include salinity (mineral salts), sediments (soil erosion), fertilizer nutrients (nitrogen and phosphorus), and bioactive materials (toxic and crop residue).

Program Accomplishments

Historically, the Irrigated Crop Production program (formerly the Irrigation Return Flow program) has looked extensively into treatment processes and structural control measures to alleviate pollution arising from irrigated crop production. An intensive study involving the U. S. Bureau of Reclamation, California Department of Water Resources, and the EPA was conducted on the Bio-Engineering Aspects of Agricultural Drainage, San Joaquin Valley, California. This project examined and evaluated treatment methods for the removal of nutrients and salinity from agricultural drainage waters. The evaluation of structural control measures has been performed primarily in the Grand Valley of Colorado. Canal lining, lateral lining, and drainage systems have been studied to evaluate the relationship between excessive seepage and the mass emission of salts to the receiving stream — in this case — the Colorado River.

Following the initial thrust of examining treatment processes and structural control measures, the program emphasis has evolved to reflect the primary importance of resource management as the key to reducing or eliminating environmental degradation caused by irrigated agricultural activities. This approach is aimed at solving the problem at the point where it is created rather than treating the effluent. Studies have been funded to evaluate the effectiveness of water, salinity and nutrient management practices on the reduction of mass emission of pollutants from irrigated lands as well as the effect on crop yields.

Aside from the obvious benefits to improve water quality, the information derived from these studies will provide a basis for development of "Best Management Practices" required in support of Section 208 of P. L. 92-500 where the states are required to submit a plan which "shall include . . . (1) a process to identify . . . agriculturally-related nonpoint sources of pollution . . . and, (2) a process to set forth procedures and methods . . . to control to the extent feasible such sources." These studies will also provide information to develop feasible effluent limitations as required for point sources in Section 301 "Effluent Limitations". Several projects have been funded to address the need for more definitive information to support the development of the NPDES irrigation return flow permits. These permits are required under Section 402 "National Pollutant Discharge Elimination System" where it is stated "the Administrator may, after opportunity for public hearing, issue a permit for the discharge of any pollutant, or combination of pollutants, . . . , upon condition that such discharge will meet either all applicable requirements under Sections 301, 302, 306, 307, 308, and 403 of this Act, or prior to the taking of necessary implementing actions relating to such requirements, such conditions as the Administrator determines are necessary to carry out the provisions of this Act."

Future Program Emphasis

During the past several years, many research and demonstration projects have been completed which have demonstrated and evaluated the effectiveness of technologies for the control of pollutants arising from irrigated agriculture. These technologies have included both structural and nonstructural measures to reduce salinity, nutrient and sediment loadings on receiving streams and/or groundwater aquifers. Economic factors and cost-effectiveness have been investigated as well. The results clearly indicate the feasibility of pollutant control at the source through improved water management and control on-the-farm. These observations lead to the question of how such controls can best be implemented in valley-wide areas and they also provide the emphasis for future directions the program should take.

Long-standing methods and practices tend to be followed year after year unchanged until it can be demonstrated that changes will result in economic gain. It follows that implementation of pollutant control measures will not be accepted and adopted until it can be shown that benefits will accrue to the user. Demonstration type projects will be required in many more of the problem areas to show the farming community what can be done in better water management, fertilizer management, etc., for irrigation return flow quality control. These must be shown to be economically feasible as well as cost-effective to reduce pollutant discharges. Projects of this type are expensive and require seceral years for successful evaluation to be completed. Educational methods, information exchange and good public relations are required to encourage acceptance of improved management practices.

Additional effort will be required to complete the needed manuals of recommended practices for the use and guidance of the state agencies responsible for planning and implementing controls over major nonpoint sources in the agricultural areas. These will be needed in regional areas where water quality problems and effective controls may differ greatly. Further analysis and methodology will be required to assess the socio-economic, legal and institutional problems facing implementation of control technologies. These must include alternative solutions and decision-making logic to arrive at equitable choices of pollutant control programs to be implemented.

As more technologies are developed, demonstrated and evaluated, the program emphasis must shift more to implementation research. Outputs of educational material, manuals of recommended practices, total system management models, and information dissemination activities must be planned into future years. The present conference is a significant effort toward passing information along to the user community. A research needs workshop will be convened immediately following this conference to identify needs and priorities for emphasis by the Irrigated Crop Production program. EPA's continued support of its ORD programs is required if we are to successfully follow through with a strong program support of the implementation of technologies which are required to show water quality improvement in our western river basins.

Nitrogen in Return Flows

7

Simulation of Nitrogen Movement, Transformations, and Plant Uptake in the Root Zone

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ABSTRACT

Two simulation models, a detailed research-type and a conceptual management-type, for describing the fate of nitrogen in the plant rootzone are discussed. Processes considered in both models were: one-dimensional transport of water and water-soluble N-species as a result of irrigation/rainfall events, microbiological N-transformations, and uptake of water and nitrogen species by a growing crop.

The research-type model involves a finite-difference approximations (explicit-implicit) of the partial differential equations describing one-dimensional water flow and convective-dispersive NH_4 *and* NO_3 *transport, along with simultaneous plant uptake and microbiological N-transformations. Ion-exchange (adsorption-desorption) of* NH_4 *was also considered. The microbiological transformations incorporated into the model describe nitrification, denitrification, mineralization and immobilization. All transformation processes were assumed to be first-order kinetic processes. The numerical solution was flexible in its soil surface boundary conditions, as well as initial conditions for soil water content and nitrogen concentration distributions in the soil profile. The solution can also be used for non-homogeneous or multilayered soil systems.*

The research-type model involves a detailed description of the individual process and requires a large number of input parameters, most of which are frequently unavailable. Because of this a more simple management-type model was developed. Several simplifying assumptions were introduced into the management model. This model requires a minimal amount of input data by the user, and provides a gross description of the behavior of various nitrogen species in the plant root zone.

INTRODUCTION

Large quantities of nitrogen are applied annually to land surfaces in the form of commercial fertilizers, animal manure, municipal and industrial waste and irrigation water. The ultimate fate of this nitrogen is of public interest because of its potential for surface water and groundwater pollution when in the nitrate form. Also, an understanding of the dynamic behavior of nitrogen in various soil-water-plant systems is essential for increasing the efficiency of nitrogen use by crops. This greater efficiency is responsible for reducing the potential for groundwater pollution by nitrates.

Various inorganic (NH_4, NO_3, NO_2, N_2O and N_2) and organic nitrogen forms exist simultaneously in the soil. These and other nitrogen substrates undergo reversible and/or irreversible transformations owing to chemical and microbiological processes. The water-soluble nitrogen species (NH_4, NO_3, and NO_2) are also transported through the soil in response to soil-water movement. The NH_4 and NO_3 distribution is complexed further by absorption by plant roots. The extent of water and nitrogen uptake is determined, in part, by the transpiration demand, which in turn is dependent upon crop growth stage and meteorological variables.

The complexity of the soil-water-plant system is further enhanced by the fact that all of

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the above processes occur simultaneously. The relative importance of any or a combination of these processes in determining nitrogen behavior is dependent not only on several physical, chemical and biological soil prperties, but also on the growth stage of the crop. Therefore, a prerequisite to modeling the fate of nitrogen in soil-water-plant systems is an understanding of the processes discussed above. A considerable amount of qualitative information is available regarding nitrogen and its agronomic aspects and individual processes in soils (Bartholomew and Clark, 1965). However, due to the nature and conditions under which much of this research was conducted, it is difficult to separate this information into a form that can be used to develop relationships useful for simulation and/or prediction purposes.

Intensive research efforts by several researchers during the past decade have yielded a multitude of models for simulation of nitrogen behavior in soil-water-plant systems. However, due to our limited understanding of the major processes and the interrelationships among them, considerable divergence exists among the modeling approaches undertaken to date. A review of the state-of-the-art of nitrogen simulation models is presented by Tanji and Gupta (1977).

In this manuscript we will describe and evaluate two nitrogen simulation models for describing the fate of nitrogen in a plant-root zone. The first is a detailed research-type model and the second a conceptual management-type model.

SIMULATION OF WATER AND NITROGEN

Three major processes that need to be considered in all nitrogen simulation models are: transport of water-soluble nitrogen species by the soil water, chemical and/or microbiological transformations, and plant uptake of water and nitrogen. The following discussion is centered around these processes.

Research-Type Model

One-dimensional water flow through saturated and unsaturated soils is described by the following nonlinear partial differential equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K_{(\theta)} \frac{\partial h}{\partial z}\right) - \frac{\partial K_{(\theta)}}{\partial z} - W_{(z,t)} \qquad [1]$$

where θ is the volumetric soil-water fraction (cm^3/cm^3), t is time (day), z is vertical distance (cm), $K_{(\theta)}$ is hydraulic conductivity (cm/day), h is soil-water potential at a given location z (cm) and $W_{(z,t)}$ represents plant root extraction (hr^{-1}). A numerical solution (finite differences by and implicit-explicit procedure) to equation [1] is presented by Selim et al. (1977a), among others.

Plant root extraction of water, $W_{(z,t)}$, was described using the Molz-Remson (1970) model:

$$W_{(z,t)} = T(t) \frac{D_{(\theta)} R_{(z,t)}}{\int_0^L D_{(\theta)} R_{(z,t)}\, dz} \qquad [2]$$

where, T(t) is evapotranspiration rate (cm/day), L is depth of root zone (cm), $R_{(z,t)}$ is "effective" plant root distribution which is proportional to root density (cm^{-2}), and $D_{(\theta)}$ is the soil-water diffusivity (cm^2/day). The total available water (TAW) for plants is defined as that held between "field capacity" and 15-bar volumetric soil-water contents. The evapotranspiration rate is equal to the potential evapotranspiration rate (PET) when the available water (AW) in the profile is greater than 20% of TAW (Ritchie, 1973). PET is obtained from the Penman equation. The value of PET was adjusted by multiplying it by a "crop factor" to account for plant growth and age during the growing season.

The movement of water-soluble nitrogen species through soils occurs as a result of molecular diffusion and mass transport in the soil-water phase. Because of the general acceptance of chromatography theory and its applicability to a soil-water system, this approach was used to describe the vertical movement and distribution of water-soluble nitrogen species. The partial differential equation for one-dimensional solute transport is:

$$\frac{\partial(\theta C_i)}{\partial t} = \frac{\partial}{\partial z} D_{(\theta,v)} \frac{\partial C_i}{\partial z} - \frac{\partial(qC_i)}{\partial z} - \rho \frac{\partial S_i}{\partial t} \pm \Phi_i \qquad [3]$$

where C_i is the solution concentration of the i^{th} nitrogen species ($\mu g/cm^3$), $D(\theta,v)$ is the dispersion coefficient (cm^3/day) which is a function of the soil-water content and average pore-water velocity ($v = q/\theta$), q is Darcy's flux (cm/day), ρ is soil bulk density (g/cm^3), S_i is adsorbed solute phase of the i^{th} nitrogen species ($\mu g/g$), and Φ_i describes the biological transformations influencing the i^{th} nitrogen species.

The mobility of the ammonium (NH_4^+) ion in a soil-water system is directly influenced and controlled by the adsorption-desorption characteristics of the NH_4^+ with the soil matrix. Numerous equations have been used to describe adsorption-desorption, but the most common are the Freundlich, first-order kinetic, and Langmuir equations (Davidson et al., 1976). Other types of cation exchange equations that could be used to describe the adsorption-desorption of NH_4^+ are described by Dutt et al. (1972). Thermodynamically based adsorption-desorption equations require more information about the composition of the soil solution than is generally available. It is believed that simpler adsorption models can be used as reasonable approximations for the adsorption-desorption of NH_4^+ in many soil-water systems.

Equations [1], [2] and [3] have been solved numerically by Selim et al. (1977b) using a finite difference (explicit-implicit) approximation technique. The solution calculates soil profile distributions of nitrogen species (NH_4, NO_3 and organic-N) as well as soil water content (or tension) at selected time intervals. The model, written in FORTRAN IV programming language, allows for water infiltration and redistribution with either a water flux or water head boundary condition at the soil surface. The nitrogen transformation processes were described by first order kinetic equations with the rate coefficients made a function of soil depth and soil water potential (h).

Assuming a linear Freundlich adsorption for NH_4^+ and first-order rate processes for the nitrogen transformations shown in Figure 1, equation [3] can be rewritten in the following form for NH_4^+ and NO_3^- in the soil solution (Selim et al., 1977b):

$$R\frac{\partial A}{\partial t} = D\frac{\partial^2 A}{\partial z^2} - \frac{V}{\theta}\frac{\partial A}{\partial z} - k_2 A - k_4 A + \frac{\rho}{\theta} k_3 O \quad [4]$$

$$\frac{\partial B}{\partial t} = D\frac{\partial^2 B}{\partial z^2} - \frac{V}{\theta}\frac{\partial B}{\partial z} + k_1 A - k_2 B - k_5 B \quad [5]$$

where A = concentration of NH_4^+ in soil solution ($\mu g/cm^3$),

B = concentration of NO_3^- in soil solution ($\mu g/cm^3$),

O = amount of N in organic phase ($\mu g/g$),

k_1, k_2, k_3, k_4, k_5 = kinetic rate coefficients, respectively, for NH_4^+ nitrification, NO_3^- immobilization, NH_4^+ mineralization, immobilization of organic-N, and NO_3^- denitrification (day^{-1}).

$V = q(z) - \theta\frac{\partial D}{\partial z} - D\frac{\partial \theta}{\partial z}$, where q(z) is the Darcy water flux (cm/day),

$R = 1 + \rho K/\theta$, retardation factor for NH_4^+ exchange,

K = distribution coefficient of NH_4^+ in exchangeable phase (cm^3/g).

The transformation processes for organic N are described by:

$$\rho\frac{\partial G}{\partial t} = k_2 \theta B + k_4 \theta A - k_3 \rho O \quad [6]$$

and the gaseous loss of N due to denitrification is calculated from:

$$\rho\frac{\partial G}{\partial t} = k_5 \theta B \quad [7]$$

where G is the sum total of N_2O, NO, and/or N_2 gas ($\mu g/g$). All transformation rate coefficients (k_i) were made a function of the soil-water potential (h) or soil-water content (θ), and/or soil organic matter content (0) at any given depth within the soil profile. These empirical relationships, similar to those used by Hagin and Amberger (1974), were devised from published data and are reported by Selim et al. (1977b).

Nitrogen uptake by plants involves the movement of water-soluble nitrogen species (NH_4 and NO_3) to the roots followed by their absorption across the root surfaces. Mass flow and diffusion are the two major processes by which NO_3 and NH_4 are transported to the roots (Nye and Spiers, 1964; Passioura and Frere, 1967; Marriott and Nye, 1968; Olsen and Kemper, 1968; Phillips et al., 1976). Convective flow of water towards roots in response to transpiration results in the transport of NH_4 and NO_3 to the roots along with the water. The concentration of these ions at the root surface decreases when the rate of root uptake exceeds the rate of supply of these ions by mass flow. Diffusion of NH_4 and NO_3 towards the roots then occurs due to the concentration gradient.

The nitrogen species taken up by plant roots are NH_4 and NO_3 (Dibb and Welch, 1976). However, due to the relatively rapid transformation of NH_4 to NO_3 and the mobility of the latter ion, most researchers have considered only the uptake of NO_3. Rao et al. (1977a) have considered the uptake of both NH_4 and NO_3 in proportion to their presence in the root zone. Data are unavailable to determine the fractional uptake of NH_4 and NO_3 by plants when both species are equally available. The maximum N-uptake demand (μg N/day/cm^2 soil surface) by the plant at any time during the growing season, denoted Q_N^{max}, was determined in a similar manner to that used by Watts (1975). The values of Q_N^{max} were determined by analyzing the cumulative N-uptake by the crop grown under non-limiting conditions for either water or nitrogen. The N-uptake rate, q_N^{max}, was calculated as follows:

$$q_N^{max} = Q_N^{max} / \int_0^L R(z,t)\,dz \qquad [8]$$

where, Q_N^{max} is defined above, the integral of R(z,t) over the rooting depth L represents the *total* root length in the profile. Note that q_N^{max} has the dimensions of μgN/day/cm root length/cm^2 soil surface/cm depth. The root capacity for N-uptake is assumed to be constant over the entire root length.

A Michaelis-Menton type relationship determined the *actual* N-uptake rate (q_N) on the basis of the soil solution concentrations of nitrate (C_{NO_3}) and ammonia (C_{NH_4}):

$$q_N = q_N^{max} \frac{C_{NO_3} + C_{NH_4}}{K + C_{NO_3} + C_{NH_4}} \qquad [9]$$

where, K is the sum of solution concentrations of NO_3 and NH_4 at which q_N equals 0.5 q_N^{max}. It should be noted that the processes (diffusion and mass flow) involved in transporting NO_3 and NH_4 to the plant roots are implicitly ignored in the approach described above. The value of q_N, calculated as in equation [9], multiplied by the root length density R(z,t) at any soil depth, yields the value for the nitrogen uptake sink term to be included in equation [3].

In the Molz-Remson (1970) plant root extraction model, the transpiration demand is expressed in units of cm water/cm root length/day. This requires a knowledge of the exact nature of root distribution in the soil profile at all times during the growing season. The water absorptive capacity of roots is assumed to be uniform over the entire root length in the model. Unfortunately, the water absorptive capacity is known to be neither uniform or constant (Newman, 1974). Models that incorporated the processes of die-off, regeneration, proliferation and extension of roots in response to soil-water stress are available in the literature (Hillel and Talpaz, 1976). For a detailed discussion of root-soil water relations and root research problems, the reader is referred to excellent articles by Barley (1970), Pearson (1974) and Newman (1974).

Empirical root growth models were devised (Rao et al., 1977a) based on measured corn (Zea mays) root length distributions in the soil profile at different times (NaNagara et al., 1976). These distributions were used as inputs in the modified Molz-Remson water uptake model (equation [1], [2])and N-uptake model (equation [8]). The root capacity for absorption of water and nitrogen was assumed uniform over the entire root length. Reduction in absorption capacity due to age or suberization was neglected. Die-off and regeneration of roots due to water stress at any given soil depth, as modeled by Hillel and Talpaz (1976), was also neglected.

In summary, the research-type model describing simultaneous one-dimensional transient water and solute transport, ion-exchange, microbiological transformations, and plant uptake of water and nitrogen is based on numerical solutions of equations [1], [3], and [9] with appropriate modifications as discussed above. Further details of this complete model and some typical simulations are reported elsewhere by Selim et al. (1977b).

Management-Type Model

The research-type model, described in the preceeding section, is conceptually pleasing in that it represents a mechanistic description of the soil-water-plant system. This model, and others like it, require extensive amounts of input data that are commonly unavailable. Also, application of these models to describe the behavior of nitrogen on large-scale watersheds does not seem feasible due to the spatial variability of the soil/plant properties. At the present time, however, the research-models are useful in performing sensitivity analyses to identify the most significant processes and/or parameters, thereby allowing for simplification. The use of simpler models becomes more desirable when only gross descriptions are required. Such a simple conceptual management-type model for describing the fate of nitrogen in the plant root zone has been described in detail by Rao et al. (1977a). Some prominent features of this model are discussed in the following paragraphs.

Several simplified forms of the transient, one-dimensional water flow model, i.e. equation [1] without the plant uptake sink term W(z,t), have been used (Dutt et al., 1972; Beek and Frissell, 1973; Duffy et al., 1976). Perhaps the most simplified concept is that "piston-displacement" used by Frere et al. (1975) and Rao et al. (1976a). This concept is based on two major assumptions: (i) all soil pore sequences participated in solute and water transport, and (ii) the soil water initially present in the profile is displaced ahead of the water entering at the soil surface. Based on these assumptions, Rao et al. (1976a) showed that the depths of wetting front (d_{wf}) and nonreactive solute front (d_{sf}) resulting from infiltration of I cm of water into the soil profile were:

$$d_{wf} = I/(\theta_f - \theta_i) \quad , \theta_f > \theta_i \qquad [10a]$$

$$d_{sf} = I/\theta_f \qquad [10b]$$

and, dividing equation [10b] by equation [10a],

$$\frac{d_{sf}}{d_{wf}} = [1 - \frac{\theta_i}{\theta_f}] \qquad [10c]$$

Published data for nitrate and chloride movement in several soils were analyzed according to equation [10c] to test its validity. These results, shown in Fig. 2, indicated that assumptions (i) and (ii) are indeed valid for a wide range of soils examined. Equation [10b] may further be extended to calculate the depth of solute front (d'_{sf}) after the soil profile had drained to a "field capacity" water content (θ_{FC}) as:

$$d'_{sf} = I/\theta_{FC} \qquad [11]$$

Finally, equation [11] was modified to consider reactive solute and the case when solute front was initially at some depth d_i in the profile,

$$d'_{sf} = d_i + \frac{I}{R\theta_{FC}} \quad , R \geq 1 \qquad [12]$$

where, R is the retardation factor due to adsorption.

Rao et al. (1976a) have also considered plant water extraction using the Molz-Remson model (equation [2]) in the above approach. The agreement between prediction and data obtained from a field study, Fig. 3, led to further improvements to include nitrogen transformations, and plant N-uptake and are discussed in detail by Rao et al. (1977a). The microbiological transformations included in the modified model were: nitrification, mineralization, and immobilization. Ion exchange of NH_4 was described by a linear isotherm. Nitrogen species resulting from transformations were estimated with analytical solutions (Rao et al., 1977b) to the differential equations describing first-order kinetic reactions. These solutions are based on the total amounts of a given nitrogen species within the soil profile and are valid under the following conditions: (1) within the region of interest, the net solute flux (input-output) in the soil profile is zero, and (ii) the soil profile is homogeneous with regard to adsorption partition coefficient for NH_4 and kinetic transformation rates. Assumption (i) can be met for deep profiles. Rao et al. (1976b) have shown that when all rate coefficients were assumed constant rather than depth-dependent,only small errors were introduced in estimating N-transformations during steady-state water flow; thus, assumption (ii) may not be limiting. Root growth and nitrogen uptake were described in a similar manner to that for the research model. However, the nitrogen uptake rate (q_N in equation 9) was determined by the total amounts of nitrate and ammonia within the root zone, rather than their concentration distributions as in equation 9. The q_N values were also adjusted when the plant was under water stress as calculated by the Molz-Remson model.

MODEL SIMULATIONS

Research Model

It is not possible to validate the research model in its entirity, as the values for all the model input parameters are not provided for in the limited data base currently available. Thus, only simulated results are presented here to demonstrate the research-model capabilities in describing the fate of nitrogen in the crop root zone. The soil parameters used in the simulations represent a well-drained loam soil, while the plant parameters are for corn crop. The simulations presented here commenced 34 days after planting and proceeded until 83 days into the crop growth season. This seven-week time period was chosen since it was the most active in terms of crop demand for nitrogen.

The initial soil-water content (θ_i) on the 34th day was assumed uniform at 0.10 cm^3/cm^3 over the entire crop root zone (0-90 cm). The soil profile was also assumed devoid of any mineral-N ($NH_4 + NO_3$), while the organic-N distribution was described by:

$$O(z) = 50.0 \ [\exp(-0.025z)] \qquad [13]$$

which amounted to a total of 2863 μg organic-N/cm ^{2} in the root zone. A solution containing 200 μg N/ml of NH_4NO_3 was applied at the surface for a period of 4 hours, followed by water application for another 8 hours (i.e., infiltration for a total of 12 hours). The soil surface was maintained saturated (h = 0) during infiltration. The total amounts of nitrogen and water applied in this manner were equivalent to 83 kg N/ha and 9 cm of water. Two additional irrigations of 3.2 and 3.3 cm of water were applied, respectively, on the 48th and 62nd day of the growing season. Water losses due to evaporation at the soil surface were ignored, while crop transpiration demand of 0.3 cm/day was assumed throughout the simulation period. Nitrate losses due to denitrification were ignored in the simulations presented here.

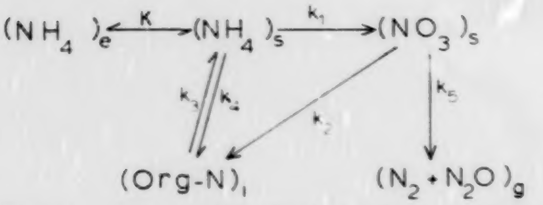

Figure 1. Soil nitrogen transformations considered in the research model. The subscripted symbol k is a first-order rate coefficient, while the subscripts e, s, i, and g refer to exchangeable, solution, immobilized, and gaseous phases, respectively. K is the Freundlich distribution coefficient.

Solution concentrations of NO_3-N and NH_4-N in the soil profile at selected times following each irrigation are shown in Figures 4 and 5. Changes in concentrations of these nitrogen species below the 60-cm depth were very small; hence are not shown. The organic-N distributions are also not presented here. The position of the NO_3-N front immediately at the end of the first irrigation (curve labeled 0.5 days in Figure 4) is at 25 cm depth and can be calculated by equation [10b] given I = 9 cm and a saturated water content (θ_f) of 0.36 cm^3/cm^3 in the wetted zone. The NH_4-N front was calculated at about 17 cm depth; this retardation is due to ion-exchange. During the two-day period following the first irrigation, redistribution of soil water had caused additional movement of both NO_3-N and NH_4-N pulses (Figures 4 and 5), respectively, to a depth of 29 and 19 cm. The total amount of NH_4-N in the soil solution had decreased during the 14-day period following irrigation (Figure 5) principally due to nitrification and plant uptake.

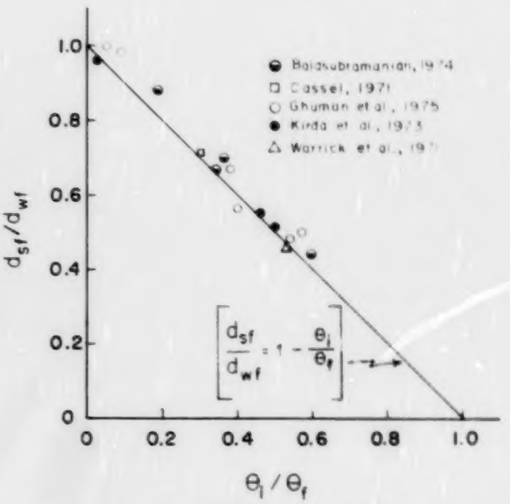

Figure 2. The relationship between d_{sf}/d_{wf} and θ_i/θ_f as calculated by Equation [10c] compared with experimental data for various sources (Reproduced from Rao et al., 1976, where references to the literature cited in this figure can be found).

A total of 43.2 cm of water was extracted from the root zone during a two-week period. This extraction resulted in an average water content of 0.21 cm^3/cm^3 in the region where NO_3-N and NH_4-N pulses resided. The second and third irrigations of 3.2 cm and 3.3 cm, respectively, were not sufficiently large to cause significant movement of these solute pulses. The total amounts of NH_4-N and NO_3-N present in the root zone continued to decrease as a result of transformations and plant uptake. NH_4-N concentrations in soil solution had diminished to less than 4 μg N/ml and that of NO_3-N were less than 10 μg N/ml by the 83rd day of the growing season (i.e., 21 days after the third irrigation).

The total amounts of NO_3-N, NH_4-N (sum of solution and exchangeable phases), and organic-N remaining in the root zone, as a percent of that at the initiation of the simulations on the 34th day, are presented in Figure 6. The losses of nitrogen shown here are due only to transformations and plant uptake, as there was no movement of soil water beyond the root zone. Rapid loss of NH_4-N is evident in Figure 6. The production of NO_3-N from nitrification was greater than that absorbed by the roots during the first week, giving rise to the plateau in the early portion of the NO_3-N curve in Figure 6. However, the amount of NO_3-N decreased rapidly after this time as NO_3-N became the sole source of N for plant uptake. There was also a small net loss of organic-N as the amount of N mineralized exceeded that immobilized during the 7-week simulation period.

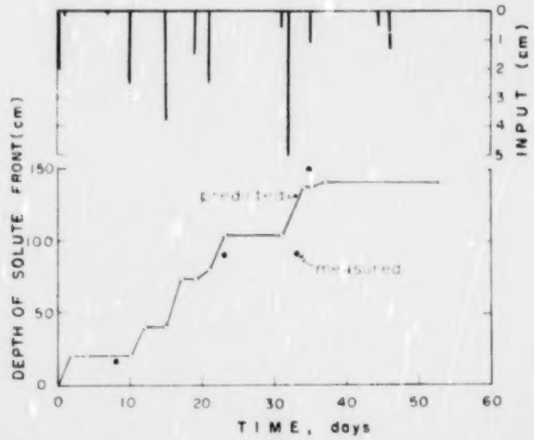

Figure 3. Comparison between measured (solid circles) and predicted (solid lines) position of the nonreactive solute front in a sandy soil at various times. The soil was planted to millet crop (Reproduced from Rao et al., 1976a).

Cumulative amount of nitrogen removed by the crop during 34-83 day growing period is shown in Figure 7. The curve marked "demand" represents the amount of N taken up by the plants if maximum N-demand ($Q_N{}^{max}$) is satisfied at all times (i.e., ideal growth). The amount of nitrogen present in the crop root zone was insufficient during the later part of the simulation period (times greater than 8 days in Figure 7) to meet the maximum demand, resulting in a significant deviation of the simulated curve from the "ideal" curve. Such a nitrogen deficit, when it occurs under real conditions, would lead to decreased dry matter accumulation and reduced yields.

Management Model

NaNagara et al. (1976) have performed field experiments to measure nitrogen uptake by corn during an entire crop growing season. In addition to measuring accumulation of N in the plant, these authors also obtained data on root length distributions, nitrate concentration and water content profiles throughout the season. These experimental data will be utilized in validation of the simple management model described earlier. NaNagara et al. (1976) have compared their data with predictions from two conceptual microscopic models of N-uptake described by Phillips et al. (1976). The first model (model I) considers the mass flow of

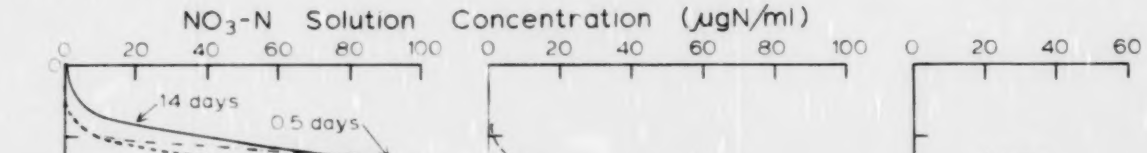

Figure 4. NO3-N solution concentrations in the soil profile, simulated by the research model at selected times following each of the three irrigations.

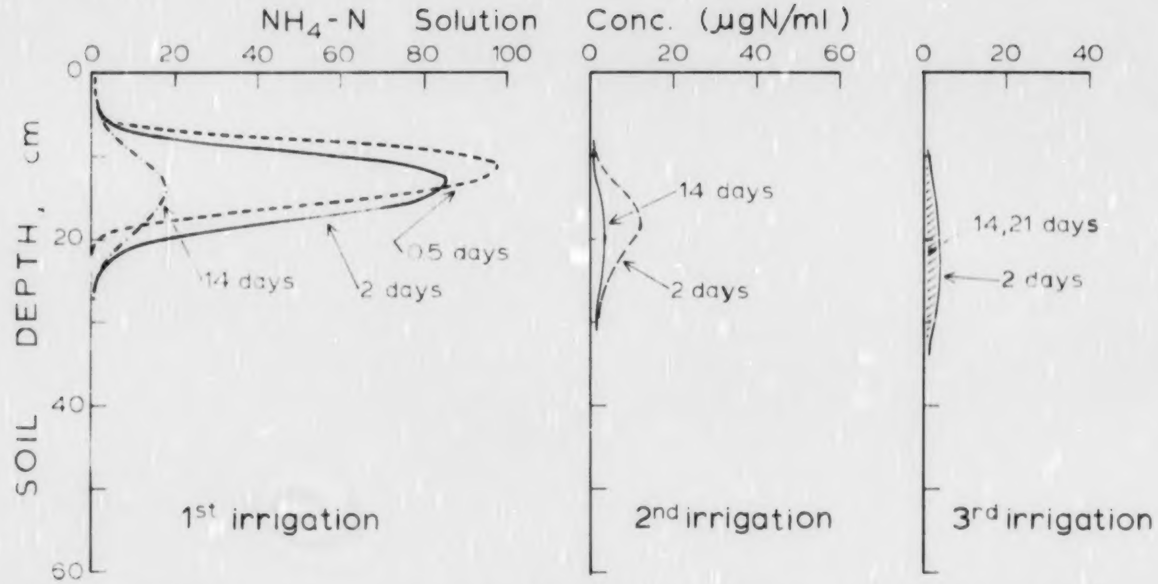

Figure 5. NH_4-N solution concentrations in the soil profile, simulated by the research model, at selected times following each of the three irrigations.

nitrate into roots with water (i.e., passive uptake) as a result of water extraction by roots in response to the transpiration demand. By knowing the amount of water transpired in a given time period and the average nitrate-N concentration in the soil solution in a given region of the soil profile, the cumulative N-uptake was estimated. Model II considers the microscopic processes of nitrate transport to root surfaces by diffusion and mass flow. Furthermore, rate of N-uptake by roots was assumed to be directly proportional to the nitrate concentration. Note that neither model I or model II consider uptake of the NH_4-N species.

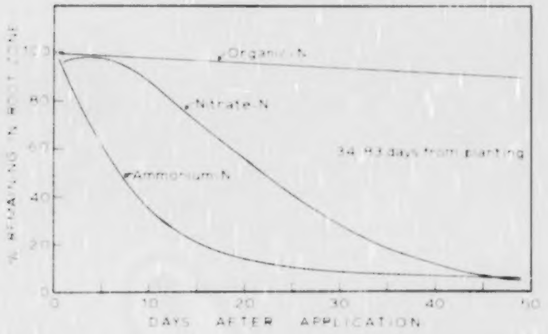

Figure 6. Percent of applied nitrogen remaining within the root zone during the simulated growth season. The curves were based on the data presented in Figures 4 and 5.

Nitrogen uptake values calculated from the simple management model are compared in Table 1 with measured values, as well as those predicted from models I and II (by NaNagara et al., 1976). Reasonable agreement between data and all three models (with widely different conceptualizations of the processes) makes acceptance or rejection of any of these models a difficult task. Considering the simplicity of model III, its close agreement with data is encouraging. However, further testing of this model with additional data is needed. When only a gross description of the nitrogen

TABLE 1

A comparison of measured nitrogen uptake by corn grown under field conditions and that predicted by three simulation models. Measured data and calculations using Models I and II are taken from NaNagra et al. (1976), while calculations using model III were presented by Rao et al. (1977a).

Growth Period (days)	*Measured N-uptake mg N/plant*	*Calculated N-uptake (mg N/plant)*		
		Model I	*Model II*	*Model III*
34-49	1435	1097	1254	1928
49-76	1593	1101	2000	1948
76-97	974	1496	1278	683
Total				
34-97	4002	3693	4533	4559
% Error		-7.7	+13.3	+13.9

behavior in the crop root zone is required, this simple model seems to hold promise.

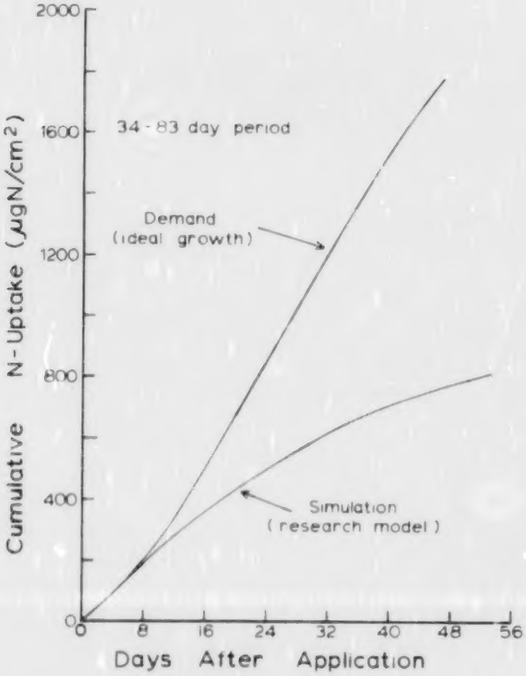

Figure 7. Comparison of the cumulative nitrogen uptake curve simulated using the research model with that when maximum uptake demand is satisfied at all times during the growth season.

ACKNOWLEDGMENT

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Nitrate Movement in Clay Soils and Methods of Pollution Control

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ABSTRACT

Movement of nitrates were measured in soils to determine quantitative amounts of losses. Leaching losses in lysimeters ranged from 0.04 to 6% depending on nitrogen source and climatic conditions. Nitrate concentrations in shallow wells within watersheds indicated that nitrates from applied fertilizer was leaching into the shallow groundwaters. Concentrations as high as 60 ppm NO_3-N were found in some wells after the initial rains following fertilization. Runoff from the watershed contained very little nitrate and amounted to less than 4% of the fertilizer applied.

A descriptive model of nitrate movement in clay soils is presented. Methods of reducing nitrate leaching in soils are discussed. Field studies indicated that inhibiting nitrification was an effective means of reducing nitrate movement from ammonium fertilizers. Slow release sulfur coated urea also reduced nitrate movement when applied in the fall or winter. Delaying fertilization until planting was also an effective means of reducing nitrate losses without reducing yields.

INTRODUCTION

Movement of nitrate is generally considered to be more of a problem in light textured sandy soils. However, it should not be misunderstood that nitrate movement is not a serious problem in clay soils. Nitrates are very soluble in water and whenever water moves through a soil, nitrate leaching can occur. In fact, Thomas and Swoboda (1969) have reported anion movement in clay soils as much as 5 times faster than would be predicted if the water moved through the soil as "piston-type" flow.

Ritchie et al. (1972) have shown that the movement of water through a clay soil which contains approximately 60% clay can be very significant. Under field conditions, they measured hydraulic conductivity values of 2.5 cm/day. Using fluorescein tagged water they illustrated that the majority of water movement was not through the entire soil matrix but rather around structural units and along cleavage planes.

In connection with this study it was also shown (Kissel et al., 1973) that Cl moved with the water and by-passed the majority of the soil structural units. They reported Cl movement to be 9 times faster than what would be anticipated under "piston-type" water movement. It is evident from these studies that water and anions do move through clay soils in significant quantities.

The importance of nitrate leaching as it relates to fertilizer losses and ground water pollution and the development of methods of reducing nitrate movement were objectives of this study.

Water Movement

The assumption is sometimes made that the water content of a soil must increase as water moves through the soil in much the same way as a water front moving through a dry soil. However, since water in clay soils in under a high capillary tension, water movement is usually rather fast. Following an irrigation or rainfall the water content of the soil surface will increase considerably since initial infiltration is rapid. However, within a few hours after infiltration is complete the moisture content of the soil surface will decrease again as the water moves through the soil. If the soil was at or near field capacity prior to the addition of the water, the moisture content of the soil below about 45 cm will change only slightly as water movement occurs. Even under ponded conditions the water content of the soil below 45 cm will seldom attain a saturated condition. Figure 1 illustrates the change in water content of Miller clay prior to and after two irrigations. The initial moisture content of the soil was a little over 5 cm of water per 15 cm of soil depth. Two days after irrigation with 9.7 cm of water, moisture readings indicated an increase in moisture content of about 0.5 cm H_2O in the top 15 cm and less than 0.2 cm / 15 cm in the next 60 cm. This moisture data indicates that over 8 cm of water had moved through the 165 cm soil profile in only two days. The second irrigation of 8.9 cm increased the moisture content slightly after 2 days, but again 8 cm of water appears to have moved through the entire profile without changing the moisture content of the soil below 60 cm.

It is evident from this data that considerable quantities of water do move through some clay soils. Nitrate leaching can be of significance in these soils when excess nitrates are present.

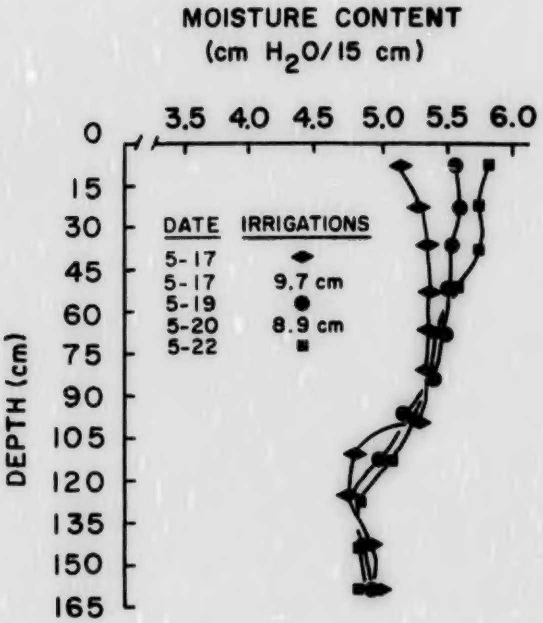

Figure 1. Moisture content of a Miller clay prior to and 2 days following 2 irrigations of 9.7 cm and 8.9 cm.

Nitrate Leaching in Clay Soils

The results of a study to illustrate nitrate leaching as a result of improper fertilization of a coastal bermuda grass pasture are shown in Figure 2. This Houston Black clay field was fertilized with 150 kg-N/ha as NH_4NO_3 on October 22, after growth had essentially stopped. During the first 2 weeks of November the field received 3 small rain storms totaling 5.7 cm. On November 21, one month after fertilization, the soil profile was sampled for nitrates. Only limited leaching had occurred (Figure 2) due to the low moisture content of the soil surface prior to the rains. Eighty percent of the applied nitrogen could be accounted for as nitrates (NO_3) in the top 45 cm of soil. In late November and early December the field received 3 additional rains, each over 2.5 cm and totaling 9.5 cm. The soil profile was sampled again on December 7, 16 days after the last sampling, and considerable leaching had occurred. Only 51% of the applied nitrogen could be accounted for in the 180 cm soil profile. The concentration of NO_3 in the top 45 cm of the soil had been reduced considerably by the ad-

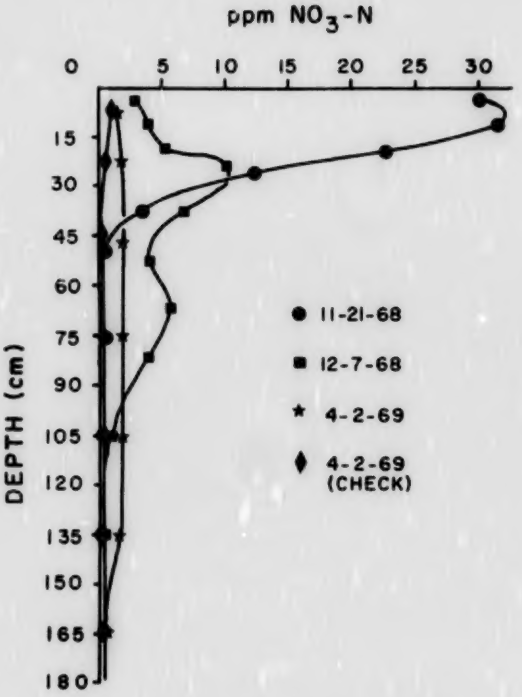

Figure 2. Concentration of NO3-N in soil profile of Houston Black clay at various times after fertilizing with 150 kg-N/ha as NH_4NO_3 on October 22, 1968.

ditional rainfall. In the spring very little available nitrogen as NO_3 for plant growth was detected in the entire profile sampled. That is not to imply that the unaccounted for NO_3 had leached through the entire 180 cm soil profile. It is believed that a large part of the unaccounted nitrogen was immobilized in the soil by microorganisms. Recent unpublished work (Kissel, 1976) has shown considerable immobilization occurs in these soils.

The movement of NO_3 through soils causes considerable concern with respect to possible contamination of shallow water supplies. Water which has a NO_3-N concentration as high as 10 ppm is generally not considered acceptable for domestic use.

Nitrates in Underground Aquifers

George and Hastings (1951) reported that about 3000 of a total of 20,000 water wells checked in Texas prior to 1948 contained over 4.5 ppm NO_3-N with many being over 400 ppm. These samples were taken prior to the widespread use of commerical fertilizers. They indicated that although most of the high nitrate wells were less than 200 feet deep, their occurence appears to be unrelated to rainfall, geography, or cultivation. Although it appears that commercial fertilizer nitrogen is not a major cause of nitrate pollution of shallow aquifers, there are some instances where leaching can contaminate shallow water supplies.

TABLE 1

Concentration of NO_3-N in shallow wells in grassland watershed at Riesel, Texas in 1974 and 1975.

	Well			
Date	*1*	*2*	*3*	*4*
10-16-73	0.1	1.0	0.2	0.2
3- 5-74	d	2.1	0.3	d
4- 1-74*	0.5	61.0	d	d
5- 7-74	9.7	20.0	0.2	d
6- 1-74	0.0	d	d	d
6-20-74	0.1	d	d	d
9- 6-74	2.3	16.5	d	d
9-13-74	0.4	d	d	d
11- 8-74*	14.4	18.8	22.6	2.8
11-20-74	6.0	d	d	d
11-27-74	4.5	5.4	d	d
12-13-74	2.8	6.2	7.1	1.6
1- 2-75	1.7	8.0	12.0	1.3
2- 5-75	0.3	2.7	3.4	0.1
2-25-75	0.0	d	d	1.2
2-27-75	0.2	2.8	d	1.8
3-16-75*	0.6	3.8	d	1.0
4-14-75	0.8	d	d	d
5- 1-75	6.0	11.2	9.9	5.7
5- 7-75*	5.3	d	d	d
5-27-75	6.0	10.2	11.2	3.7
6-11-75	33.0	d	d	0.4
7- 3-75	20.5	d	d	0.2
7-28-75	4.0	d	d	d

*90 kh/ha of nitrogen as NH_4NO_3 was applied on March 5 and September 27, 1974, and on March 16, and May 7, 1975.

d-well was dry

A study was initiated to measure the movement of nitrates with runoff water from a watershed and leaching within the watershed. Water samples were collected and runoff measured from a 7.7 ha grassland watershed. Water samples were periodically obtained from 4 shallow wells installed in the watershed. The wells were placed at a depth to intercept water moving along the semi-impermeable calcareous marl layer underlying the Houston Black clay. The wells were generally between 1.8 and 2.4 meters deep. Nitrogen as NH_4NO_3 was applied twice each year at the rate of 90 kg-N/ha.

Runoff from the watershed which amounted to 31 cm in 1974 and 15.6 in 1975, contained very little nitrates. Generally, the concentrations in the runoff during the 2 year study were less than 1 ppm NO_3-N, although one storm following a fertilizer application of 90 kg-N/ha produced runoff which had concentrations as high as 7.2 ppm NO_3-N. The total amount of NO_3-N which was carried off the watershed in 1974 was less than 1 kg/ha, and in 1975 the amount lost was 6.5 kg/ha.

Of the 4 wells installed in the watershed, only one contained water at all times during the two year study. The other 3 wells only contained water intermittently following rainy periods. The concentration of nitrates were generally very low in all wells. The only exception was after the initial leaching rain following each application of fertilizer nitrogen. Table 1 shows the concentrations in the wells at various times during the 2-year study. It is readily evident that fertilization of the pasture did increase the NO_3 concentration in the wells. The highest concentration observed was 61 ppm NO_3-N in Well 2 on April 1, 1974. However, all 4 wells did show indications of nitrates leaching.

Well 1, which always contained water and appeared to intercept a dependable water supply for domestic use, contained NO_3-N levels exceeding 10 ppm during 2 periods of the study; these were in November of 1974 and June and July of 1975. Both of these periods closely followed applications of fertilizer nitrogen. It is important to note that the concentrations decreased rapidly after each of these periods indicating dilution within the aquifer was occurring.

It appears that leaching of fertilizer nitrogen into these shallow aquifers can and does occur. However, the quantity of nitrate which is leached appears to be small and dilution within the aquifer can reduce the concentrations within a short period of time.

Methods of Controlling Nitrate Leaching

A study was initiated in the fall of 1973 to determine the effectiveness of several systems for reducing nitrate movement in clay soils. Since it is well documented that nitrates can readily move through soils which do not have a significant anion adsorptive capacity, the basic premise of this study was to devise methods of maintaining fertilizer nitrogen in the ammonium form (NH_4) as long as possible. The ammonium form of nitrogen can be adsorbed by the negatively charged sites on the clay and restrict its movement through the soil.

TABLE 2

Total NO_3-N and NH_4-N in 120 cm profiles of Houston Black clay fertilized with different sources of nitrogen and treated with N-Serve and sampled January 21, 1975.

*Treatment**	*Oct. 18*		*Nov. 19*		*Dec. 20*		*Reduction in NO3*
	NO3-N	*NH4-N*	*NO3-N*	*NH4-N*	*NO3-N*	*NH4-N*	
			kg-N/ha				%
Soluble N	433	0	362	18	179	154	—
SCU	221	26	316	12	80	78	37
Soluble N + N-Serve	127	88	117	52	77	327	67
SCU + N-Serve	160	66	257	98	112	62	46

(*Date of Application* spans Oct. 18, Nov. 19 and Dec. 20.)

***Soluble N are average of $(NH_4)_2SO_4$ and urea treatments, CSU are average of SCU-20 and SCU-30 treatments.**

Three basic techniques were investigated for maintaining fertilizer nitrogen in the ammonium form until plant utilization. The first technique consisted of treating ammonium forms of fertilizers with a specific microbicide which inhibits the nitrification process in soils. This method would delay the conversion of NH_4 to NO_3. The second technique was the use of slow release or slowly soluble nitrogen sources which would limit the amount of NH_4 and NO_3 which would be present in the soil at any time. The third system investigated was the timing of nitrogen application with regard to plant utilization.

These three systems were investigated at two locations on two different soils and for a period of two years. One soil was a silt loam (Norwood, Typic Udifluvent) and the other a clay (Houston Black, Udic Pellustert). The field plots on Norwood silt loam were located in the flood plain of the Brazos River near College Station, Texas and the field plots on Houston Black clay were located at the Blackland Research Center near Temple, Texas.

TABLE 3

Total NO_3-N and NH_4-N in 120 cm profiles of Houston Black clay on June 6, 1975 after fertilizing with soluble sources and slowly soluble sources of nitrogen with and without treatment with N-Serve.

Date of application	*Oct. 18*		*Nov. 19*		*Dec. 20*		*Feb. 21*		*Mar. 25*		*Reduction in NO3*
*Treatment**	*NO3-N*	*NH4-N*	*NO3-N*	*NH4-N*	*NO3-N*	*NH4-N*	*NO3*	*NH4*	*NO3*	*NH4*	
					kg-N/ha						%
Soluble N	268	[illegible]	[illegible]	–	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SCU	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Soluble N + N-Serve	208	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22
SCU + N-Serve	[illegible]	[illegible]	[illegible]	[illegible]	128	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

***Soluble N are average of $(NH_4)_2SO_4$ and urea treatments, SCU are average of SCU-20 and SCU-30 treatments.**

The treatments at each location consisted of two readily soluble nitrogen sources (ammonium sulfate and urea) and two slowly soluble nitrogen sources, both sulfur coated ureas (SCU-10 and SCU-30). The numerical values after each refer to the percentage of nitrogen soluble in hot water (38°C) during 7 days of incubation. Each nitrogen treatment was also applied with a nitrification inhibitor, N-Serve [2-chloro-6 (trichloromethyl-pyridine)]. The inhibitor was applied directly to the fertilizer at a rate equivalent to 1% of the total nitrogen. Each fertilizer was applied at a rate of 134 kg-N/ha (120 lbs-N/ac) in a band 12-18 cm below the furrow. Fertilizers were applied each month **starting in October and continuing until planting time in March. Each treatment was replicated three times. Grain Sorghum *(Sorghum***

***vulgare)* was planted each year on both soils as the indicator crop. Soil core samples were taken through the placement band to a depth of 120 or 150 cm twice each year to monitor nitrate movement in the soils.**

There was no significant difference between the ammonium sulfate and urea sources of nitrogen as to their effect on NO_3 movement and therefore, will be discussed together and referred to as Soluble N. There was a little difference between the two sulfur-coated ureas with the more soluble form (SCU-30) resulting in more NO_3 movement. However, both sources were similar enough so that they can be discussed as one source.

The rate of nitrification in the Houston Black clay soil as affected by source of nitrogen, treatment with N-Serve, and time of applying nitrogen is shown in Tables 2 and 3. Soil samples taken during the Winter (Jan. 21, 1975) had very little NH_4 remaining in the soil from the soluble sources of nitrogen except for the December application. Since the December application was made only one month prior to sampling, it would be expected that considerable NH_4 would remain in the soil. Even though the nitrogen was in the soil only a short time, and with the cool winter temperatures, over 50% of the nitrogen had been nitrified (Table 2). It is evident that nitrification is very active in the Houston Black soil.

The use of sulfur coated urea (SCU) reduced the amount of NO_3 present in the soil at any time during the 3 months by 37%. The lower total amount of nitrogen reported for the SCU sources was due to unhydrolyzed sulfur-coated urea prills remaining in the soil.

The nitrification inhibitor was very effective during the winter months in reducing the amount of NO_3 present in the soil. Even when the treated soluble sources were applied 3 months prior to sampling 40% of the nitrogen present remained in the less leachable NH_4 form. The amount of NO_3 present in the soil at any time during the 3 months was reduced 67% by the N-Serve treatment (Table 2).

The data in Table 2 depict a significant decrease in the total amount of inorganic nitrogen present in soil from the N-Serve treatment. This effect was evident at both research sites and during each year of the study.

Jansson (1958) has reported that NH_4 is much more readily utilized by microorganisms than is NO_3. The use of a nitrification inhibitor with an NH_4 fertilizer maintains a higher concentration of NH_4 in the soil for a longer period of time, thereby enabling more nitrogen to be immobilized. Thus, the decrease in inorganic nitrogen shown in Table 2 for the N-Serve treatments.

Treatment of the SCU's with N-Serve also reduced the amount of NO_3 present in the soil at any one time, although it was not as effective as the treatment of the Soluble N source.

The summer sampling on June 6, 1975 of the Houston Black clay typifies the effects of fertilizer timing and nitrification. Table 3 illustrates that nitrification of the soluble NH_4 sources was very rapid and complete. No NH_4 remained in the soil in June from any of the dates of application of the soluble N sources. As in the winter samples the slowly soluble sources (SCU) reduced the amount of leachable NO_3 in the soil at any given time. There was an average of 41% **less** NO_3 in the soil from the SCU treatments as compared to the ammonium sulfate and urea treatments. Undissolved sulfur coated prills and some NH_4 still remained in the soil on June 6 even when the SCU was applied the previous October.

TABLE 4

Amount of NO_3-N leached below 60 cm but above 120 cm in Houston Black clay on January 21, 1975 as influenced by nitrogen source, nitrification inhibitor and time of application.

*Treatment**	*Date of Application* *Oct. 18*	 *Nov. 19*	 *Dec. 20*	*Reduced Leaching*
		kg-N/ha		%
Soluble N	128†	92	48	—
SCU	88	64	36	30
Soluble N + N-Serve	60	68	40	38
SCU + N-Serve	68	72	44	32

***Soluble N are average of $(NH_4)_2SO_4$ and urea treatments, SCU are average of SCU-20 and SCU-30 treatments.**

†NO_3 content of control plots have been subtracted from these values.

Treatment of the nitrogen sources with the nitrification inhibitor also reduced the amount of NO_3 present in the soil in June for all dates of application. There was a considerable amount of NH_4 present in the soil even when the nitrogen was applied in October, indicating the N-Serve still had some inhibitory effect 7 months after application. The effect of N-Serve in reducing nitrification was reduced somewhat during the warmer part of the year as indicated by the 22% average reduction in NO_3 content in June as compared to the 67% average reduction found for the soluble source in January (Table 2). There was very little difference between the two soils at the different locations in relation to the different treatments.

It is apparent that the use of slowly soluble nitrogen sources and the treatment of fertilizer with N-Serve were effective in reducing the amount of leachable NO_3 present in the soil at any time. Therefore it would seem that these practices would also be effective in reducing the quantity of nitrate leaching through soils.

The amount of NO_3 found below 60 cm in the sampled profiles was found to be a good indicator of nitrate leaching. Time of application had a great influence on the amount of NO_3 found below 60 cm in both the silt loam and clay soil. The winter samples on January 21, 1975 indicated that considerable movement of NO_3 had already occurred into the zone below 60 cm for all treatments (Table 4). Since the mineralized NO_3 found in the control plots was taken into account to obtain the values in Table 4, the values shown are a result of the fertilizer applied. The earlier applications of nitrogen caused considerable more NO_3 to move below 60 cm. Even the December application, which was made only 30 days prior to sampling, resulted in NO_3 movement below 60 cm.

The slow release sources and treatment with N-Serve reduced the amount of NO_3 movement, but they did not prevent leaching even when applied only 30 days prior to sampling. The NO_3 found below 60 cm represents a significant portion of the total NO_3 in the profile. Generally, about 35% of the NO_3 in the profile was found below 60 cm at the January sampling.

TABLE 5

Amount of NO_3-N leached below 60 cm but above 120 cm in Houston Black clay on June 6, 1975 as influenced by nitrogen source, nitrification inhibitor, and time of application.

*Treatment**	*Oct. 18*	*Nov. 19*	*Dec. 20*	*Feb. 21*	*Mar. 25*	*Reduced Leaching*
	Date of Application					
	Kg-N/ha					%
Soluble N	171†	78	62	60	48	—
SCU	48	51	29	34	34	53
Soluble N + N-Serve	58	57	48	30	49	42
SCU + N-Serve	32	61	24	28	30	58

*Soluble N are average of $(NH_4)2SO_4$ and urea treatments, SCU are average of SCU-20 and SCU-30 treatments.

†NO_3 content of control plots have been subtracted from these values.

In June of 1975 the effect of fertilizer timing on NO_3 movement was more evident than in January (Table 5). Fertilization with the soluble sources of nitrogen in the fall resulted in much more NO_3 being present below 60 cm than when fertilizer was applied in the spring. However, this effect was not near as evident for the other treatments, although the amounts of NO_3 found below 60 cm was reduced by 42-53% by the use of SCU and N-Serve treatment of ammonium sulfate and urea. The percentage of total NO_3 in the profile found below 60 cm in June ranged from as high as 63% from the October application to as low as 16% in the March application. It is very likely that some NO_3 had already moved below the depth of sampling in June since samples taken between 120-150 cm contained considerable amounts of nitrates.

The use of sulfur coated urea and treatment of urea and ammonium sulfate with a nitrification inhibitor appear to significantly reduce the amount of NO_3 leaching in both the clay and silt loam soils. However, these treatments did not have any affect on the yield of grain sorghum. Although, it appeared that considerable leaching did occur, probably less than 15% of the applied nitrogen actually moved below the rooting zone of the grain sorghum. The 134 kg-N/ha applied appears to be more than required for maximum yields even when considering 15% loss by leaching.

SUMMARY

Nitrate movement in clay soils can be of significant magnitude. Pollution of underground water supplies is possible when nitrogen fertilizers are improperly used and excessive rates are applied.

The use of slow release nitrogen sources, and the treatment of readily soluble nitrogen sources with an effective nitrification inhibitor, can reduce the amount of nitrate movement through soils. Applying nitrogen fertilizers to the soil as near to the time when plants can utilize it will also reduce the chances for pollution of underground water supplies.

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Effect of Three Irrigation Systems on Distribution of Fertilizer Nitrate Nitrogen in Soil

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ABSTRACT

Sweet corn (Zea Mays L.) was grown two years on a Miles loamy fine sand (Udic Paleustalfs) fertilized with band applied ^{15}N *enriched sodium nitrate. Two plots, 6 x 6 m, were established under each of the three irrigation systems - sprinkler, furrow and subirrigation. A starter band of fertilizer was applied 7.6 x 7.6 cm from the seed with the rest sidedressed 25 cm either side of the center of the seedbed. Total nitrogen applied was 124 kg/ha in 1973 and 105 kg/ha in 1974. In 1974, each of the six plots that were established in 1973 were divided in half, one half receiving* ^{15}N *enriched fertilizer as sodium nitrate, and the other half receiving the same amount of unenriched sodium nitrate. Soil samples were taken periodically from furrow to furrow in lateral distance increments of 25 cm and through the starter fertilizer band to a depth of 5.2 m in 30 cm increments. Plant samples were obtained at the end of each growing season. Soil and plant samples were analyzed using standard procedures.*

Fertilizer nitrogen moved differently under the three irrigation systems. When sprinkler-irrigated, fertilizer bands tended to maintain their integrity during downward movement. Under furrow irrigation, fertilizer bands tended to merge in the center of the bed and move downward. Under subirrigation, fertilizer tended to move down under the furrows. At the end of two crop years, greatest depth movement of fertilizer nitrogen was under sprinkler irrigation and least under subirrigation. Additionally, a greater amount of fertilizer nitrogen was found in the organic nitrogen fraction under the sprinkler system than under the furrow system with the subirrigation system having the least.

The amount of nitrate-nitrogen from fertilizer to a depth of 5.2 m was found to be in the order: sprinkler > furrow > subirrigation. At the end of two crop years, it was possible to account for 92.6, 86.1, and 50.5 percent of the fertilizer nitrogen applied to the sprinkler, furrow, and subirrigation systems, respectively. The largest differences between irrigation systems, in accounting for applied fertilizer nitrogen during the two years, occurred in the soil.

The amount of fertilizer nitrate remaining in the upper portion of the profile for the longest period of time was subirrigation > furrow > sprinkler. The retention of nitrate in the upper portion of the profile in conjunction with high water potentials resulted in denitrification. The amount of denitrification was apparently greatest for subirrigation and least for sprinkler irrigation. The quality of irrigation return flow, relative to nitrates, to underground water was in the order: subirrigation > furrow > sprinkler.

INTRODUCTION

Application of fertilizer nitrogen to sandy soils low in organic matter is necessary for sustained high levels of production. However, movement of fertilizer nitrate-nitrogen through porous soils into shallow underground water strata has been considered to be a potential pollution hazard, particularly under irrigation. The purpose of the study reported here was to determine the effects of three irrigation

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systems — sprinkler, furrow and subirrigation — on the movement of fertilizer nitrate-nitrogen in the presence of a growing crop.

METHODS AND MATERIALS

Sweet corn (*Zea Mays L.*) was grown two years on a Miles loamy fine sand (Udic Paleustalfs) fertilized with band applied ^{15}N enriched sodium nitrate. Two plots, 6 x 6 m, were established under each of the three irrigation systems-sprinkler, furrow and subirrigation. A starter band of fertilizer was applied 7.6 x 7.6 cm from the seed with the rest sidedressed 25 cm either side of the center of the seedbed. Total nitrogen applied was 124 kg/ha in 1973 and 105 kg/ha in 1974, Table 1. In 1974, each of the six plots that were established in 1973 were divided in half, one half receiving ^{15}N enriched fertilizer as sodium nitrate and the other half receiving the same amount of unenriched sodium nitrate. The bands were flagged and soil samples were taken periodically from furrow to furrow in lateral distance increments of 25 cm and through the starter fertilizer band to a depth of 5.2 m in 30 cm increments. The plant samples were obtained at the end of each growing season. Soil and plant samples were analyzed using standard procedures (1, 2).

TABLE 1

Dates and amounts of nitrogen as ^{15}N enriched sodium nitrate applied to experimental plots.

Date	*Starter*	*Sidedress*
	Nitrogen (kg/ha)	
May 5, 1973	32.3	
June 4, 1973		91.3
March 24, 1974	22.4	
June 6, 1974		82.4

Irrigation water amounts applied for the three systems for both years are shown in Table 2. The sprinkler and subirrigation systems received approximately the same amount of irrigation water both years. Somewhat more water was applied to the furrow system due to the fact that in the loamy fine sand soil, 75 mm of water had to be applied in order to obtain uniform distribution. Rainfall date are shown in Table 3. There was a large variation in the amount of rainfall received during the crop growing seasons. A substantial amount of rain was received between harvest of the 1973 crop and planting of the 1974 crop.

TABLE 2

Dates and amounts of irrigation water applied to sprinkler, furrow and sub-irrigated plots.

Irrigation System	*Year* 1973	1974
	Water (mm)	
Sprinkler	256	249
Furrow	381	310
Subirrigation	256	255

TABLE 3

Dates and amounts of rainfall received from planting in 1973 to last sampling in 1974.

Time of Year	*Year* 1973	1974
	Rainfall (mm)	
Before Planting		15
Growing Season	104	193
After Harvest	275	

RESULTS AND DISCUSSION

Distribution of fertilizer nitrate for 1973 in the sprinkler-irrigated plots is shown in Table 4. On the first sampling date of May 31, the starter band of fertilizer was detected in the top 30 cm sampling increment. Subsequent samplings throughout the growing season show that the fertilizer nitrate tended to move down through the soil in distinct bands. Also, it will be noted that after the first sampling date that little or no fertilizer nitrate was detected in the top 30 cm. Maximum depths to which fertilizer nitrate was detected were in the 90 to 120 cm sampling increment. Fertilizer nitrate concentration decreased with time and tended to move down in the profile. The reduction in the amounts detected was probably due to leaching, plant uptake, immobilization and denitrification.

A somewhat different distribution pattern of fertilizer nitrate can be seen for the furrow-irrigated plots, Table 5. Again, the starter band was detected at the first sampling date in the top 30 cm of soil. Concentrations tended to decrease with time and the fertilizer nitrate moved down in the profile with the detectable amounts being found in the 120 to 150 cm sampling increment which was somewhat deeper than for the sprinkler-irrigated plots. Also, the fertilizer

TABLE 4

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two spinkler irrigated plots fertilized with ^{15}N enriched sodium nitrate, 1973.

Samp. Depth	*Lateral Sampling Distance (cm)*					
(cm)	*0*	*25*	*51*	*58*	*76*	*102*
	Nitrate-N (ppm)					
	May 31, 1973					
0-30	0.0	0.0	0.0	29.4	0.0	0.0
30-60	0.0	0.0	0.0	6.1	0.0	0.0
60-90	0.0	0.0	0.4	0.8	0.0	0.0
	June 22, 1973					
0-30	0.0	2.7	0.0	0.0	0.0	0.0
30-60	0.0	59.8	3.7	3.8	21.0	0.0
60-90	0.0	24.7	6.2	8.5	7.8	0.0
90-120	0.0	3.3	0.4	2.7	0.2	0.0
120-150	0.0	0.1	1.1	0.4	0.0	0.0
	July 26, 1973					
0-30	0.0	0.0	0.0	0.0	0.0	0.0
30-60	0.0	0.0	0.0	0.0	0.0	1.2
60-90	0.0	1.1	1.7	8.4	0.0	0.0
90-120	0.0	0.2	0.2	0.0	0.0	0.0
120-150	0.0	0.0	0.0	0.1	0.0	0.0
150-180	0.0	0.0	0.0	0.0	0.0	0.0
180-210	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 5

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two furrow irrigated plots fertilized with ^{15}N enriched sodium nitrate, 1973.

Samp. Depth	*Lateral Sampling Distance (cm)*					
(cm)	*0*	*25*	*51*	*58*	*76*	*102*
	Nitrate-N (ppm)					
	May 31, 1973					
0-30	0.0	0.0	3.4	28.3	0.0	0.0
30-60	0.0	0.0	0.0	1.8	0.0	0.0
60-90	0.0	0.0	0.0	1.0	0.0	0.0
	June 22, 1973					
0-30	0.0	0.3	3.8	16.0	2.2	1.7
30-60	2.0	5.0	7.5	19.0	1.3	1.8
60-90	2.0	2.4	3.8	2.0	0.8	2.0
90-120	0.0	1.4	3.0	3.8	0.1	0.8
120-150	0.0	0.0	0.0	0.0	0.0	0.0
	July, 28 1973					
0-30	0.0	0.0	0.2	0.0	0.2	0.2
30-60	0.1	0.0	0.0	0.0	0.0	5.8
60-90	1.2	0.2	0.3	6.4	2.2	3.0
90-120	4.8	2.2	1.6	9.5	2.6	0.4
120-150	0.2	3.3	1.6	4.2	0.1	0.0
150-180	0.0	0.5	0.4	0.5	0.0	0.2
180-210	0.0	0.0	0.0	0.0	0.1	0.0
210-240	0.0	0.0	0.0	0.0	0.0	0.0

nitrate tended to move toward the center of the bed and to move downward at this point. It will be noted that substantial quantities of fertilizer nitrate were detected in the top 30 cm of the soil through the third sampling date.

Fertilizer nitrate distribution for the subirrigated plots for 1973 is shown in Table 6. This distribution pattern is considerably different from the other two systems in that the fertilizer nitrate tended to move outward from the center of the bed and toward the furrows. This was a consequence of the fertilizer bands being placed above and 25 cm either side of the subirrigation lateral. Thus, movement of irrigation water was always upward and toward the furrows with respect to the fertilizer bands. It will be noted that detectable quantities of fertilizer nitrate were found in the top 30 cm of the soil through the third sampling date and that it did not move in detectable quantities below 90 cm.

Distribution of fertilizer nitrate for the sprinkler-irrigated plots for 1974 is shown in Table 7. At the first sampling date on May 22, the fertilizer nitrate from the starter band was detected to a depth of 90 cm. It was probably located deeper in the soil in 1974 than in 1973 due to the greater amount of rainfall that fell between its application in 1974 and the first sampling date than for the same period in 1973. Additionally, some quantities of fertilizer nitrate were found in a depth range of 180 to 300 cm and was apparently that applied in 1973. At this sampling date, the sidedressed bands were detected in the upper 30 cm of soil along with some additional downward movement of the starter band. Also, fertilizer applied in 1973 had moved downward an additional 30 cm. By the last sampling date on July 16, further movement downward of the 1974 sidedressing and starter fertilizer bands can be seen in the upper portion of the soil profile and of the 1973 fertilizer nitrate in the lower portions of the profile. It is interesting to note the zone of extremely low concentrations from 150 to 240 cm that resulted in a distinct separation between fertilizer nitrate applied in 1973 and that applied in 1974.

Concentrations of fertilizer nitrate for the samples taken from the furrow-irrigated plots in 1974 are shown in Table 8. Again, the starter band of fertilizer was detected at the first sampling date to the depth increment of 60 to 90 cm probably due to additional amounts of rainfall received between application and first sampling in 1974 as opposed to 1973. Additional amounts of fertilizer nitrate were detected at lower depths (90 to 210 cm); somewhat higher in the profile than for the sprinkler plots. At the second sampling date on June 20, the two sidedressed band applications were detected in the top 30 cm of soil with some evidence of movement downward and depletion of the starter band fertilizer in the upper portions of the profile. The distinction between fertilizer applied in 1973 and 1974 was not as clear for the furrow-irrigated plots as for the sprinkler-irrigated plots. There was additional movement downward of fertilizer nitrate as determined by the soil sampling on July 17. There was also depletion of fertilizer nitrogen probably due, in addition to leaching, to plant uptake, immobilization and denitrification. The more diffuse pattern with a lack of distinct separation between the fertilizer applied in 1973 and 1974 was probably due to the fact that the fertilizer nitrate was held in the upper portions of the profile longer under a furrow system than under a sprinkler system. The fertilizer was applied in a band in the bed at a vertical placement above the bottom of the water furrow. Water moving into and upward in the bed carried the fertilizer

TABLE 6

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two subirrigated plots fertilized with ^{15}N enriched sodium nitrate, 1973.

Samp. Depth (cm)	*Lateral Sampling Distance (cm)* 0	25	51	58	76	102
	Nitrate-N (ppm)					
	May 31, 1973					
0-30	1.3	0.8	4.5	32.0	0.0	0.2
30-60	1.8	0.0	0.1	0.2	0.0	0.0
60-90	0.0	0.0	0.0	0.0	0.0	0.0
	June 22, 1973					
0-30	7.4	6.8	17.1	19.4	1.6	10.5
30-60	0.4	2.0	0.2	0.5	0.0	0.1
60-90	0.0	0.1	2.2	0.2	0.4	1.0
90-120	0.0	0.0	0.0	0.0	0.2	0.0
120-150	0.0	0.0	0.0	0.0	0.0	0.0
	July 28, 1973					
0-30	0.0	0.0	0.0	0.1	0.2	0.0
30-60	0.0	0.0	0.0	0.0	0.2	0.5
60-90	0.0	0.0	0.0	0.0	0.0	0.0
90-120	0.0	0.0	0.0	0.0	0.0	0.0
120-150	0.0	0.1	0.0	0.0	0.2	0.0
150-180	0.0	0.5	0.0	0.0	0.2	0.0
180-210	0.0	0.5	0.0	0.0	0.0	0.0
210-240	0.0	0.2	0.0	0.0	0.0	0.0

TABLE 7

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two sprinkler irrigated plots fertilized with ^{15}N enriched sodium nitrate, 1974.

Samp. Depth (cm)	*Lateral Sampling Distance (cm)* 0	25	51	58	76	102
	Nitrate-N (ppm)					
	May 22, 1973					
0-30	2.0	0.2	1.6	2.0	0.2	0.2
30-60	0.6	0.2	4.4	2.6	0.6	0.2
60-90	0.4	0.2	1.8	0.2	0.3	0.2
90-120	0.5	0.2	0.2	0.2	0.2	0.1
120-150	0.8	0.3	0.1	0.4	0.2	0.2
150-180	0.4	0.2	0.3	0.0	0.2	0.1
180-210	1.0	0.3	0.2	0.2	0.2	0.2
210-240	2.9	0.4	0.2	0.2	0.2	0.2
240-270	0.3	0.6	0.2	0.0	0.5	1.0
270-300	1.3	0.4	0.4	0.0	0.5	0.3
	June 18, 1974					
0-30	0.3	7.2	0.0	12.7	24.4	0.1
30-60	0.5	0.1	1.0	0.8	0.2	0.1
60-90	0.5	0.2	3.8	2.5	0.3	0.2
90-120	0.4	0.5	0.6	1.3	0.3	0.3
120-150	0.6	0.6	0.5	0.3	0.2	0.2
150-180	0.5	0.7	0.5	0.5	0.4	0.1
180-210	0.3	0.4	0.4	0.2	0.3	0.2
210-240	0.7	0.2	0.3	0.2	0.1	1.1
240-270	2.7	1.0	0.4	1.0	0.0	1.5
270-300	2.1	2.5	2.3	2.9	0.1	1.4
330-360	0.1	0.4	1.1	0.7	0.1	0.1
	July 15, 1974					
0-30	0.2	0.5	0.5	3.4	6.4	0.3
30-60	0.2	7.6	1.3	7.4	4.8	0.5
60-90	0.2	3.3	2.2	4.6	1.4	0.6
90-120	0.2	1.2	2.1	4.0	0.7	0.6
120-150	0.2	0.5	0.6	0.7	0.3	0.4
150-180	0.3	0.5	0.4	0.3	0.2	0.2
180-210	0.4	0.5	0.6	0.6	0.5	0.6
210-240	0.2	0.3	0.5	0.7	0.6	0.8
240-270	0.6	1.3	1.8	2.6	0.6	2.0
270-300	3.0	1.4	1.5	1.8	1.1	1.0
300-330	1.0	0.8	0.6	0.5	1.0	0.6

along. Thus, fertilizer movement in the furrow system was affected by irrigation water moving upward as well as downward and rainfall moving downward. Where all the water movement under the sprinkler system was straight down, the fertilizer nitrate tended to move the same way under both irrigation and rainfall resulting in the distinct separation of 1973 and 1974 applied fertilizer.

TABLE 8

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two furrow irrigated plots fertilized with ^{15}N enriched sodium nitrate, 1974.

Samp. Depth	*Lateral Sampling Distance (cm)*					
(cm)	*0*	*25*	*51*	*58*	*76*	*102*
	Nitrate-N (ppm)					
	May 20, 1974					
0-30	0.3	0.3	0.8	0.2	0.2	0.3
30-60	0.2	0.6	15.4	5.0	1.4	0.1
60-90	1.0	2.4	2.0	0.4	0.2	0.0
90-120	1.6	3.4	0.4	0.9	0.3	0.0
120-150	1.5	2.0	1.0	0.8	0.4	0.2
150-180	0.2	0.5	1.2	1.5	0.5	0.2
180-210	0.2	0.5	1.2	1.8	0.2	0.2
210-240	0.2	0.6	0.5	0.0	0.2	0.0
	June 20, 1974					
0-30	0.2	44.0	5.6	16.1	0.8	0.3
30-60	0.6	20.3	4.2	5.8	0.4	0.3
60-90	0.6	2.2	3.0	1.6	0.4	0.5
90-120	1.0	3.4	4.5	3.0	0.2	0.6
120-150	4.5	6.2	7.6	5.8	0.5	0.8
150-180	4.8	7.0	4.3	4.4	0.9	3.5
180-210	3.1	5.7	5.4	3.7	2.6	3.8
210-240	0.8	2.4	1.6	1.4	0.8	2.0
240-270	0.1	0.4	0.4	0.3	0.2	0.4
270-300	0.0	0.2	0.2	2.2	0.0	0.2
300-330	0.0	0.0	0.0	2.7	0.0	0.0
330-360	0.0	0.2	0.0	1.0	0.0	0.0
360-390	0.0	0.0	0.0	0.0	0.0	0.0
	July 17, 1974					
0-30	1.5	5.6	0.7	3.2	0.3	0.5
30-60	2.7	3.6	0.7	6.1	2.1	0.5
30-60	0.9	1.7	1.8	3.0	1.2	0.8
90-120	1.2	8.1	4.0	0.8	0.5	0.8
120-150	1.9	5.5	2.7	1.1	0.2	0.7
150-180	1.2	3.0	2.0	0.6	0.8	0.3
180-210	3.2	4.3	3.2	0.9	0.8	0.7
210-240	2.1	5.5	3.5	1.2	0.4	0.6
240-270	0.4	1.4	2.0	0.8	0.2	0.1
270-300	0.4	0.6	0.6	0.2	0.0	0.2

Data from the subirrigated plots for 1974 are shown in Table 9. The movement pattern is different than for the two previously discussed plots and somewhat similar to that in 1973 wherein the fertilizer nitrate was generally held up in the profile. At the first sampling date on May 16, the fertilizer nitrate from the starter band was detected with only small quantities of fertilizer nitrate other than that found in the profile. The sidedressing bands were detected in the upper 30 cm of the profile at the second sampling date and by the third sampling date it

TABLE 9

Average fertilizer nitrate-N concentrations for three sampling dates by depth and lateral sampling location for two subirrigated plots fertilized with ^{15}N enriched sodium nitrate, 1974.

Samp. Depth	*Lateral Sampling Distance (cm)*					
(cm)	*0*	*25*	*51*	*58*	*76*	*102*
	Nitrate-N (ppm)					
	May 17, 1974					
0-30	0.5	0.5	0.3	2.2	0.0	0.2
30-60	0.7	0.5	1.0	0.6	0.4	0.2
60-90	0.6	0.2	7.9	9.5	0.7	0.2
90-120	0.7	0.6	0.0	0.0	0.2	0.0
120-150	0.4	1.2	0.1	0.0	0.0	0.0
150-180	0.4	0.5	0.2	0.7	0.2	0.0
	June 14, 1974					
0-30	2.4	17.2	0.0	0.0	20.5	0.2
30-60	0.6	0.6	0.0	0.0	0.2	0.4
60-90	0.5	1.9	0.0	0.6	0.1	1.2
90-120	6.0	0.4	1.4	0.4	0.2	2.1
120-150	1.6	0.9	0.2	0.1	0.6	2.0
150-180	3.3	0.6	0.4	0.4	0.6	1.8
180-210	2.0	2.0	0.0	1.4	0.3	0.6
210-240	0.7	0.2	0.0	1.6	0.3	0.4
240-270	0.3	0.1	0.0	1.0	0.2	0.4
270-300	0.0	0.3	0.0	0.9	0.2	0.5
	July 18, 1974					
0-30	3.8	0.8	0.2	0.2	0.2	2.8
30-60	1.5	0.1	0.0	0.0	0.1	0.2
60-90	0.2	1.2	0.0	0.0	0.0	0.0
90-120	0.4	0.4	0.5	0.0	0.0	0.1
120-150	0.2	0.3	0.0	0.0	0.0	0.0
150-180	0.4	0.6	0.0	0.0	0.0	0.2
180-210	0.4	1.8	0.0	0.1	0.0	0.2
210-240	0.4	1.2	0.0	0.2	0.0	0.2
240-270	0.1	1.2	0.1	0.3	0.0	0.2
270-300	0.6	1.3	0.1	0.4	0.0	0.4
300-330	2.0	0.9	0.1	0.2	0.0	0.5
330-360	1.8	0.3	0.1	0.2	0.1	0.7
360-390	1.0	0.2	0.1	0.2	0.1	0.8
390-410	0.4	0.2	0.1	0.2	0.2	1.0

had moved outward under the furrows. There was some small amount of leaching of fertilizer nitrate in the profile along with decreases in concentration due to the same reasons given previously. The indications for the subirrigation system are that fertilizer nitrate was held higher in the profile for longer periods of time than for either the furrow or sprinkler systems due to the upper movement of the irrigation water.

Utilizing soil analyses data and plant analyses data from 1974, it was possible to account for 92.6, 86.1 and 50.5 percent of the fertilizer nitrate applied over the two-year period for the sprinkler, furrow and subirrigation systems, respectively. Thus the indications are that denitrification was greatest under subirrigation, next under furrow irrigation and least under sprinkler irrigation. The distribution of fertilizer nitrate in the soil profile would tend to confirm this in that it was held higher in the profile in a position where the soil microorganisms responsible for denitrification could have a readily available energy source in the order: subirrigation > furrow irrigation > sprinkler irrigation. Tensiometer data indicated that the upper portions of the soil profile were maintained at water potentials of -20 cb or greater for substantial periods of time. Field capacity for this particular soil has been determined to be -10 cb.

In summary, some general statements can be made about the movement of fertilizer nitrate under these irrigation systems. The banded fertilizer under the sprinkler system tended to move straight down in the profile, apparently somewhat more rapildy than for the two other irrigation systems. Thus, the sharp distinction between the 1973 and 1974 applications. For the furrow irrigation system, with the band applied above the bottom of the water furrow, the direction of water flow and subsequent movement of fertilizer nitrate apparently was such that it held the fertilizer nitrate up in the profile somewhat longer than for the sprinkler system even with greater water application rates. The fertilizer tended to merge in the center of the bed and then to move downward, either with the movement of irrigation water or rainfall. Thus, the more diffuse pattern of vertical distribution and less distinct break between 1973 and 1974 applied fertilizer. For subirrigation, the fertilizer nitrate apparently moved upward and outward from the bands to a position next to the furrow or under the furrow due to the movement of the irrigation water that came from beneath and to the side of the fertilizer bands. Movement downward apparently occuurred due to some irrigation water and rainfall.

While apparently a number of factors affected fertilizer nitrate movement, including rainfall between the crop years, crop utilization, denitrification and immobilization, there is no doubt that the method of irrigation played a major role in the movement of fertilizer nitrate-nitrogen in this study.

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Nitrogen and Water Management to Minimize Return-Flow Pollution from Potato Fields of the Columbia Basin

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ABSTRACT

Cooperative field studies have evaluated levels of dissolved soil N, and corresponding crop yields, for selected potato production practices in the Columbia Basin area of Washington. High dissolved-N levels were found throughout the growing season in well-managed potato fields. Such levels were decreased by decreased fertilization rate, use of slow-release N fertilizers, or sprinkler-application of N fertilizers.

Careful water management during sprinkler irrigation proved capable of maintaining dissolved-N within the root zone of subsequent crops by season's end, even on very sandy sites. Alternate-furrow irrigation also proved effective in "trapping" much banded fertilizer N within the plant root zone on heavier-textured furrow-irrigated soils. Periodic recovery of residual N by other crops in the rotation is necessary to prevent eventual return-flow contamination, however.

Site-to-site sampling variability necessitated the use of composited soil samples, rather than fixed-position soil solution extraction cups, for adequate monitoring of dissolved-N levels in soils of the area. Neither dissolved soil N nor plant petiole NO_3-N proved to be reliable predictors of crop N needs at the high residual soil N levels commonly found in recropped potato fields of the Columbia Basin.

INTRODUCTION

In addition to return-flow contamination of surface streams, agricultural practices in irrigated areas can lead to significant return-flow contamination of area groundwaters. Of particular concern is the rapid leaching of nitrates from soils whenever water in excess of crop needs is allowed to percolate. A test crop of particular sensitivity to fertilizer and water management techniques is the potato, because of its concurrent requirements of high fertility and high soil moisture levels. Field studies of nitrate leaching in conjunction with various soil, crop and water management practices were carried out in the Columbia Basin area of central Washington, largely with Environmental Protection Agency funding from 1970 through 1974. This 200,000 hectare irrigation project is largely responsible for the fact that the state of Washington is second in the nation in total potato production, and leads the nation in potato production per acre. Hence, the potato serves as a significant and sensitive indicator crop for the area.

METHODS AND MATERIALS

Initial sampling of soil solutions from potato-producing fields was carried out through the use of ceramic extraction cups placed at 8 to 12 locations in each field. These cups generally were placed at the 30, 60, 120 and 240 cm soil depths, as well as immediately above the basalt or caliche layer underlying the field. A portable vacuum pump was used to produce a vacuum of approximately 0.4 bar at each sampling site, with a small butane tank being used as a vacuum buffer and attached through a manifold system to each set of cups. Soil solution extraction was terminated for each depth after 50 to 100 ml of solution had been obtained from the appropriate extraction cup, or after 24 hrs had elapsed since irrigation. Samples were stored in a refrigerator at approximately 4°C until analysis.

As the large field variability from sampling site to sampling site became evident, decreasing reliance was placed upon fixed-position sets of extraction cups, and greater reliance was placed upon variable-position soil sampling for obtaining estimates of soil solution nitrate concentrations and amounts of nitrate leaching within irrigated potato fields. Soil samples were collected by hand with a King tube sampler during the cropping season, and either with a King tube or with an hydraulic Giddings sampler at season's end. Samples were placed in 250- or 500-ml plastic cartons for transport the same day to the laboratory in Pullman. Samples were then frozen until they could be dried prior to analysis. Drying was in a convective drying oven at 60°C for 24 hrs. Samples were then ground to pass a 2mm sieve and stored until analyses could be performed on 2:1 water:soil extracts. Extracts were clarified by centrifugation, after a 10-minute extraction period on a reciprocating shaker.

Total dissolved inorganic nitrogen in extraction cup extracts or soil sample extracts was measured with a steam distilliation method employing MgO and Devarda's alloy (Bremner, 1965). Most of this nitrogen was in the nitrate form, as identified by combining the above steam distillation procedure with one employing MgO alone during the initial phases of the study. In addition, sample pH and electrical conductivity were measured with a standard laboratory pH meter and conductivity cell, respectively, and chloride was measured potentiometrically with a commercial chloridimeter.

Initial studies during 1970 and 1971 of the project period were carried out at an extremely sandy site in Block 21 of the Columbia Basin project. Many soils of this unit had initially been passed over for irrigation development because their sandy nature was incompatible with the surface irrigation systems employed on most initially-developed lands of the Columbia Basin Project. They are subsequently being developed using solid-set or center-pivot sprinkler irrigation systems. Field studies at this location were carried out in connection with workers from the WSU Irrigated Agriculture Research and Extension Center at Prosser, Washington, with joint funding from the U.S. Bureau of Reclamation (Middleton et al, 1975). The stratified sands and sandy loams at this location were underlain by basalt at a depth of 2.4 to 3.1 meters. A water table developed at the surface of the basalt beneath plots receiving excessive water applications.

Remaining studies were carried out in cooperation with Dr. R. Kunkel of the Department of Horticulture of Washington State University. Many of the studies were carried out at the WSU Othello Field Station on a silt loam soil typifying many of the first lands developed for the Columbia Basin Project. Such soils are commonly furrow-irrigated, although sprinkler irrigation is being practiced increasingly on these soils as well. The soil at the Station is commonly 1 to 1.5 meters in depth, and underlain by caliche hard pan.

Studies were also carried out during the 1973 season at four locations in grower's fields. The fields were arrayed in a 150-kilometer arc extending from a location in the Horse Heaven Hills area south of Pasco and Kennewick (just north of the Oregon border) to a location east of Moses Lake in the northern portion of the Columbia Basin. All locations were managed by the growers themselves, although differentially-fertilized, planted and harvested by WSU workers. They thus provided an estimate of potential ground water and drainage water contamination under "real world" operating conditions.

Most experimental plots throughout the studies were ten to fifteen meters long and 2 to 4 rows (1.6 to 3.2 meters) wide. Four to six replicates normally were included at each location for each set of management conditions studied.

RESULTS AND DISCUSSION

Sandy Site

Typical results from the extraction cup samplings at the sandy experimental site are presented in Table 1. Except for cases where excessive leaching of fertilizer nitrogen occurred (e.g., during late season for the high-rate furrow-irrigated plots), soil solution dissolved N values were commonly in the range of several tens to a few hundreds of mg per liter. This contrasts with the maximum drinking water standard of 10 mg/l for dissolved NO_3-N. Shallow ground waters in extensive potato producing areas thus might commonly be expected to develop NO_3-N values in excess of the

TABLE 1

Average soil dissolved inorganic N values, and tuber yields, sandy site, 1969-1971.

Treatment	*Depth*	*Average Dissolved N Values*[a]					*Mea-sure*	*Average Tuber Yields*		
		Apr 20 -May 5	*June 4-11*	*July 3-8*	*Aug 5-12*	*Sept 4-9*		*110 kg N/ha*	*330 kg N/ha*	*560 kg N/ha*
	(cm)		(mg/liter)						(quintals/ha)	
Low-rate Sprinkler	0-120	40	76	73	234	298	Total	446	554	587
(Q1)[b]	120+	68	33	70	113	78	No 1's	379	414	413
High-rate Sprinkler	0-120	139	105	296	132	54	Total	450	553	617
(Q3 = 1.5 x Q1)	120+	45	48	36	160	33	No 1's	383	475	481
Low-rate Furrow	0-120	56	195	512	85	26	Total	—	389	387
(W1)	120+	206	20	162	123	12	No 1's	—	221	155
High-rate Furrow	0-120	83	310	68	9	2	Total	—	368	379
(W3 = 3 x W1)	120+	16	16	48	5	3	No 1's	—	205	192

[a] Ceramic extraction cup data, 5 to 8 data per average.

[b] Q1 = replacement of ET, using evaporation pan estimates. W1 = time to wet to mid-furrow at mid-run (122-meter run).

drinking water standard. Alternate water sources may be required in such areas for young infants and nursing mothers. The data of Table 1, as well as the data of most subsequent tables of this report, demonstrate that the potato is not an efficient nitrogen-utilizer. Soil solutions at the end of the growing season in potato-producing fields still commonly contain several tens of mg/l of NO_3-N (see also Kirkham et al, 1973). This is in contrast to results for efficient nitrogen utilizers, such as wheat (Fanning et al, 1969). This is probably one reason why high empirical fertilizer requirements have been developed for this crop.

The low-rate sprinkler application (approximately 75 surface-cm of water) was sufficient to produce near maximal yields at this site (Jensen et al, 1961). Slight increases in total tuber yield, and somewhat larger increases in yield of U.S. #1 tubers at the site with higher sprinkler application rates, probably result from compensation for wind distortion of solid-set sprinkler patterns at the site. Some localized water stress undoubtedly developed under the windy late-spring and early-summer conditions for the low-rate sprinkler treatment.

The low-rate sprinkler treatment maintained most fertilizer nitrogen in the surface 120 cm of soil until season's end. This nitrogen thus would be available for "scavenging" by subsequent deep-rooted crops in the rotation. The high-rate sprinkler treatment led to decreased dissolved-N values for the surface 120 cm of soil near season's end. As yields were not increased substantially, and as soils at the site appear to be too sandy for much denitrification at this water application rate, the decrease probably reflects nitrogen leaching to the greater depths. Such leaching may account for the increased nitrogen concentrations at the greater depths for this application rate on the August sampling date. The data are far from unequivocal, however, and reflect a common problem with the use of ceramic extraction cups for field studies involving realistic depth increments and sampling periods. Substantial amounts of solute can be present in the soil between extraction cup depths at any one extraction time, and yet go essentially undetected. Leaching of nitrogen to depths between the 240-cm and 300-cm positions, or dilution of leached nitrogen with low-N waters in the water table at the 300-cm depth, could easily produce the anomalously-low subsoil dissolved-N levels of the early September sampling period.

As expected, the studies demonstrate that use of furrow irrigation on such extremely sandy sites would lead both to substantial leaching of nitrogen and also to substantially lower crop yields. Sprinkler irrigation had been at 1 to 3 day intervals during the study period, and furrow irrigation was at 2 to 4 day intervals, with the selected interval being shortened for each successive year of the study. The pattern of nitrogen leaching to greater soil depths is clearly evident from the data for the low-rate furrow-irrigated plots, where dissolved-N values decreased progressively after early July for samples from the surface 120 cm of depth. Substantial amounts of nitrogen were present at the greater soil depths (well beyond the rooting depth of potatoes) on both the July and August sampling dates. This water application rate (averaging 350 surface cm of water) had virtually depleted the soil profile of dissolved-N by the end of the irrigation season. At the high rate of furrow irrigation (averaging 920 surface cm of water), root-zone dissolved-N values decreased rapidly after early June. The entire profile was leached essentially free of nitrogen by early August at this water application rate.

In addition to problems with site-to-site variability and solute placement between extraction cup depths, an additional problem at this sandy site was the fact that all extraction cups did not yield solution on every sampling date. As a result, variable sample populations were included on many dates. This was not as great a problem for finer-textured sites, but subsequent sampling placed increasing reliance on soil sampling in place of extraction cup usage.

Silt Loam Site

In 1972, all sampling was carried out at the Othello Field Station of Washington State University, on a silt-loam soil (McNeal and Kunkel, 1973). As evident from the data for the four experiments summarized in Table 2, root zone dissolved-N values at season's end were commonly on the order of several tens of mg/l. As root zone dissolved-N values generally decreased during the growing season, because most nitrogen in these experiments had been banded or broadcast at planting time, this indicates that even higher nitrogen concentrations are probably present in most waters percolating from these fields. For example, the subsoil under a long-term fertilizer factorial experiment (Table 2-d) increased 3-fold in dissolved-N levels over a five year period at the highest nitrogen application rate. Soils at this site commonly develop a tillage or traffic pan at the 20 to 40 cm depth during potato production (Gardner et al, 1975). Such pans are typical of many potato-producing areas of the Columbia Basin. Water flux estimates based on tensiometer data fell in the range of 0.02 to 0.2 cm per day for this location during 1972. These values are quite low in relation to soil texture and existing irrigation practices, and probably reflect the influence of the compacted layer. Such water flux estimates can be combined with values for dissolved nutrient concentrations to provide estimates of the quantities of nutrients being leached under various farm management regimes. For example, a flux of 0.1 cm per day for a 120-day growing season corresponds to 12 surface cm of water, or to 59 kg of N per hectare at an average dissolved-N level of 50 mg/l.

The data of Table 2 generally substantiate the trends of increased root zone dissolved-N levels at higher nitrogen application rates and/or lower water application rates. The lower subsoil dissolved-N values at the head of furrow-irrigated fields (Table 2-a) may reflect either greater leaching of nitrogen from the subsoil with greater amounts of water passage through the profile, or increased tendency for denitrification at these relatively shallow depths at higher average water contents. As a basis of comparison for data of the table, commercial nitrogen applications of 300 to 400 kg of N per hectare are common for potatoes in the Columbia Basin area at present, and values of 500 to 600 kg of N per hectare are not uncommon for sandy soils irrigated with center-pivot systems, where nitrogen can be applied through the irrigation line throughout the irrigation season. Although levels of dissolved-N were higher at the higher nitrogen fertilization rates, there was not a linear relation between nitrogen application rate and nitrogen concentration of the soil solution. Substantial amounts of nitrogen remained in the soil solution at season's end even at low nitrogen application rates, and levels were increased only two to three fold even when the nitrogen fertilization rate was increased five to six fold.

An interesting observation from Table 2-c is the maintenance of high levels of dissolved-N in the root zone even after the over-winter period following the 1971 suspension experiments. By the fall of 1972, however, with the ground left fallow during the summer of 1972, root zone dissolved-N levels had decreased markedly. This probably reflects incorporation of dissolved-N into organic forms, for little irrigation water had been applied prior to the fall 1972 sampling, and the ryegrass cover crop then being grown on the plots had not developed sufficiently to utilize much of the nitrogen which was present. As indicated earlier, subsoil dissolved-N levels under long-term fertilizer plots were in the neighborhood 150 mg/l for a 450 kg N/ha fertilization rate (Table 2-d). Because of the poor utilization by potatoes of applied nitrogen, however, subsoil dissolved-N values were on the order to 50 mg/l even at extremely low nitrogen application rates. This substantiates the potential for ground water and drainage water contamination by returnflows from potato-producing areas.

Grower's Fields

Data of Tables 3 and 4 demonstrate results from the sampling of grower's fields during the 1973 season. Once more, dissolved nitrogen levels of several tens to a few hundred mg/l were common in all cases, except for the furrow-irrigated sandy site near Moses Lake where leaching of nitrogen from the subsoil was apparent once it "escaped" entrapment in root zone soil during alternate-furrow irrigation

TABLE 2

Average soil dissolved inorganic N values, silt loam site, 1972.

Experiment	*Depth*	*Average Dissolved N Values* [a]			
	(cm)	*(mg/liter)*			
a) Furrow-rate		Head of Field		Tail of Field	
		High Water[b]	Low Water	High Water	Low Water
	0-60	30	38	49	104
	60+	6	13	31	93
		Low N[c]	High N	Low N	High N
	0-60	21	47	64	88
	60+	9	10	36	88
b) 1972 Suspension Fertilizer		Broadcast		Banded	
		110 kg N/ha	670 kg N/ha	110 kg N/ha	670 kg N/ha
	0-60	37	89	38	54
	60+	21	43	23	42
c) 1971 Suspension Fertilizer		Spring of 1972		Fall of 1972	
		110 kg N/ha	670 kg N/ha	110 kg N/ha	670 kg N/ha
	0-60	80	174	15	24
	60+	32	105	39	67
d) Long-term Fertilizer Factorial		Nitrogen Plots		P and K Plots	
		0-100 kg/ha[d]	450 kg/ha	0-100 kg/ha	450 kg/ha
	0-60	63	44	44	63
	60+	49	147	106	102

[a] Soil sampling data, generally post-harvest.

[b] 122-meter run, wetting alternate sides of a given crop row every 6 or 2 days.

[c] 220 or 450 kg N/ha.

[d] Annually as N, P_2O_5 or K_2O for 1965-1967 and 1970-1971. 480 kg N/ha to all plots in 1972.

TABLE 3

Averages and variations in soil dissolved inorganic N values, and tuber yields, suspension fertilizer trials, grower's fields, 1973.

				Average Dissolved N Values[a]				*Average Tuber Yields*			
Location	*Soil*	*Irrigation System*	*Depth*	*Early Season*		*Late Season*		*Total*		*No 1's*	
				F1[b]	*F4*	*F1*	*F4*	*F1*	*F4*	*F1*	*F4*
			(cm)	(mg/liter)				(quintals/ha)			
Tri-Cities Area	Silt Loam	Center-pivot	0-60	193	401	121	178	—	—	—	—
			60+	52	48	39	68				
Horse-Heaven Hills	Sand	Center-pivot	0-60	177	204	48	154	451	454	409	411
			60+	56	68	61	127				
Moses Lake	Sandy Loam	Alternate-furrow	0-60	124	293	52	120	466	539	278	296
			60+	12	26	8	13				
Othello	Silt Loam	Solid-set	0-60	155	367	43	101	731	743	431	381
			60+	95	121	69	111				

				Coeff. of Variation, dissolved N Values (%)					
				Late Season		Early Season		Late Season	
				F1	F4	Ba	Br	Ba	Br
Tri-Cities Area	Silt Loam	Center-pivot	0-60	98	103	72	70	91	110
			60+	66	101	65	69	69	98
Horse-Heaven Hills	Sand	Center-pivot	0-60	65	111	74	88	—	88
			60+	72	41	67	53	—	56
Moses Lake	Sandy Loam	Alternate-furrow	0-60	98	102	92	104	92	107
			60+	112	147	107	96	112	148
Othello	Silt Loam	Solid-set	0-60	96	95	104	106	91	99
			60+	111	124	66	101	115	121

[a] Soil sampling data.

[b] F1 and F4 = 110 and 450 kg/ha N, P2O5 and K2O at the Tri-Cities site, 250 and 520 kg/ha at the Horse-Haven Hills site, and 110 and 450 kg/ha at the Moses Lake and Othello sites, respectively.

(where adjacent furrows are never wet simultaneously during the growing season). The use of alternate-furrow irrigation still maintained reasonably high dissolved-N levels in the plant root zone at this site until late season, however. Once more, dissolved-N values increased with increasing fertilizer application rate, and decreased during the growing season, at each location. Nitrogen was applied through the irrigation line, in addition to pre-plant applications to all experimental plots, for each of the center-pivot locations. Use of slow-release nitrogen sources (Table 4) led to substantial reductions in root-zone and subsoil dissolved-N values early in the season at each location. By late season, however, there commonly remained more dissolved-N in root-zone soils from the slow-release nitrogen plots than from those fertilized with traditional nitrogen sources. Thus, subsequent crop management would be extremely important where slow-release nitrogen sources were used to minimize ground water or drainage water contamination in potato-producing areas.

As was commonly observed throughout the study period, only slight responses to nitrogen fertilization in excess of 200 to 300 kg of N per hectare were evident in most cases. In fact, yield of U.S. No. 1 tubers was commonly decreased by increasing nitrogen application rate. Such data, when coupled with the above-mentioned commercial fertilization rates, suggest that excess nitrogen is being applied for potato production in much of the Columbia Basin area at the present time. One reason for this may be that nitrogen recommendations developed for new potato lands are being maintained as lands revert to nearly-continuous potato production, despite the facts that somewhat lower yields are obtained (even with annual fumigation) under continuous production and that nitrogen release during subsequent growing seasons from prior crop residues may constitute an appreciable source of nitrogen. One exception to this trend of decreasing yields with increasing fertilization rate occurred at the Moses Lake site, where furrow irrigation of a sandy site was apparently leading to enough nitrogen leach-

TABLE 4

Average soil dissolved inorganic N values, and tuber yields, slow-release N experiments, grower's fields, 1973.

				Average Dissolved N Values[a]				*Average Tuber Yields*			
Location	*Soil*	*Irrigation System*	*Depth*	*Early Season*		*Late Season*		*Early Season*		*Late Season*	
				Trad[b]	*SR*	*Trad*	*SR*	*Trad*	*SR*	*Trad*	*SR*
			(cm)	(mg/liter)				(quintals/ha)			
Horse-Heaven Hills	Sand	Center-pivot	0-60	469	352	150	226	385	412	318	325
			60+	83	51	105	64				
Moses Lake	Sandy Loam	Alternate-furrow	0-60	256	128	95	94	484	434	263	231
			60+	18	9	14	12				
Othello	Silt Loam	Solid-set	0-60	296	162	85	146	719	712	503	502
			60+	84	50	71	57				
Othello Station	Silt Loam	Alternate-furrow	0-60	354	265	236	154	606	655	361	392
			60+	81	23	100	32				

[a] Soil sampling data.

[b] Traditional N sources = NH_4NO_3, $(NH_4)_2$ and SO_4 and urea. Slow-release sources = sulfur-coated ureas SC 100, SC 45 and SC 25.

ing losses to maintain a yield response at higher nitrogen application rates.

Average tuber yields were commonly as high or even slightly higher for slow-release nitrogen sources, reflecting the somewhat greater maintenance of nitrogen levels throughout most of the growing season for plots to which such fertilizer materials had been applied. An exception was the alternate-furrow site at Moses Lake, where slow-release nitrogen sources apparently did not release nitrogen fast enough to meet the nitrogen needs of the crop under conditions where appreciable leaching of fertilizer nitrogen occurred.

The data at the bottom of Table 3 demonstrate the high degree of variation that is evident in field dissolved-N values. Coefficients of variation were commonly in the range of 75 to 100% of the means for all field studies. Contrary to earlier expectations, coefficients of variation were not substantially lower for sprinkler-irrigated than for alternate-furrow-irrigated fields, for broadcast fertilizer applications than for banded fertilizer applications, or for subsoil than for root zone samples. The amounts of variation in such field studies are simply large, and have to be compensated by large numbers of composited samples if one is to obtain reliable estimates of nitrate leaching patterns on a field-wide basis.

Additional Studies

Table 5 presents data obtained from studies at the Othello Field Station of Washington State University during 1973. In the nitrogation experiment, nitrogen was applied through the irrigation line at various fertilization rates and application intervals. The data of the table represent nitrogen application at two rates and in equal amounts either every two weeks or every six weeks of the growing season. Highest yields were obtained at the lower nitrogen fertilization rate and at the most frequent nitrogen-application interval. Minimum soil dissolved-N nitrogen concentrations remained at about the same levels as observed in the other fertilization studies, as would be anticipated from the above-noted inefficiency of potatoes with respect to nitrogen uptake. The maxima in soil dissolved-N levels were considerably less in these nitrogated plots, however. This approach appears promising as a method for lowering leaching losses of nitrogen from sprinkler-irrigated potato fields. Fortunately, it is already common usage in the Columbia Basin area.

The second study summarized in Table 5 consisted of an evaluation of several sprinkler-irrigation rates at the silt loam site. A fertilization-rate study was superimposed. Both total yields and yields of U.S. No. 1 tubers were nearly constant whether water was applied at only 75% of estimated ET needs (Jensen et al, 1961) or at rates as high as 150% of estimated needs. Somewhat higher yields were obtained at the higher fertilization rates in this particular set of studies. This is contrary to common trends on recropped potato lands in the Columbia Basin, and may reflect the growth of a crop

TABLE 5

Average soil dissolved inorganic N values, and tuber yields, silt loam site, 1973.

Experiment	*Depth Measure*	*Average Dissolved N Values*[a]									
		Early Season				*Late Season*					
		F2[b]	*F4*	*2 week*	*6 week*	*F2*	*F4*	*2 week*	*6 week*		
	(cm)	(mg/liter)									
Nitrogation	0-60	102	33	49	59	76	89	74	111		
	60+	71	17	39	20	40	22	29	33		
				Average Tuber Yields (quintals/ha)							
				F2	F4			2 week	6 week		
	Total			709	643			710	646		
	No 1's			513	461			493	471		
		Average Dissolved-NJ Values (mg/liter)									
		Early Season					Late Season				
Irrigation Rate		F1&2[c]	F3&4	75%	100%	150%	F1&2	F3&4	75%	100%	150%
	0-60	280	729	290	583	640	26	108	153	22	26
	60+	30	129	96	39	103	15	139	112	91	30
				Average Tuber Yields (quintals/ha)							
				F1&2	F3&4	75%	100%	150%			
	Total			646	680	664	653	673			
	No 1's			491	516	493	500	518			

[a] Soil sampling data

[b] F2 and F4 = 340 and 670 Kg N/ha, respectively. Applied in equal increments every 2 or 6 weeks.

[c] F1 and F2 = 110 & 220 kg N/ha. F3 & F4 = 450 & 670 kg N/ha. Sprinkler irrigation at 75, 100 or 150% of estimated ET, based on microclimatological estimates.

having a high nitrogen requirement on this particular field of the Othello Station during the preceeding season. Early season root-zone dissolved-N values were extremely high in this study, but late season root-zone, and entire season subsoil, dissolved-N levels were typical of values obtained from our other studies as well.

As several studies had indicated that excess nitrogen was being applied to many potato fields of the Columbia Basin area, studies were carried out in 1973 and 1974 to evaluate the amounts of soil and plant nitrogen required for maximum crop yields, and to evaluate various parameters which might be used to estimate crop yield from soil or plant nitrogen analyses. Results of these studies are summaried in Table 6. In the 1973 studies, crop yields were correlated with root zone dissolved-N levels or with plant petiole NO_3-N values at various times during the growing season. Except for the Moses Lake site, where nitrogen stress developed because of some nitrogen leaching, no correlation was obtained between yields and either soil nitrogen or petiole NO_3-N values on any of four dates throughout the growing season. Correlations were commonly negative, indicating that lower yields were obtained at higher soil or plant nitrogen levels.

For the 1974 studies, a series of plots were established at the WSU Othello Field Station in which an attempt was made to maintain plants at various petiole NO_3-N levels throughout the entire growing season. As petiole NO_3-N levels tended to decrease with increasing physiological age of the crop, it was only possible to maintain the different levels on a *relative* basis. However, the results of the study suggest that attempts to maintain 10,000 ppm petiole NO_3-N until mid-August may be *one* local practice accounting for excessive nitrogen fertilization in much of the Columbia Basin area. Of the various petiole NO_3-N levels and petiole sampling dates examined, only the intermediate NO_3-N levels for the 90-day sampling date proved well related to total tuber yield or yield of U.S. #1 tubers. Maintenance of petiole NO_3-N levels of 10,000 to 12,000 ppm until approximately mid-July would have produced maximum yields in this particular case. However, maintenance of such high levels further into the growing season provided no demonstrable correlation with either total yield or yield of U.S. #1 tubers.

When the same data were evaluated in a different manner, as outlined in the bottom portion of Table 6, no "critical" petiole NO_3-N levels were apparent. If such a level were present, then yields should have been depressed as the amount of time increased during which the crop was below this critical level. No such trends were evident, either for entire-season petiole data or for petiole data to August 15th. This was true even when petiole NO_3-N levels had dropped as low as 5,000 ppm. Plants grown for substantial periods at petiole NO_3-N levels less than 5,000 ppm produced yields as high or higher than plants which had never been allowed to decrease below this petiole level. Thus, the use of a critical petiole NO_3-N value of 10,000 ppm for potatoes being grown in the Columbia Basin does not appear to be warranted, except possibly as an early-season indicator of adequate soil nitrogen levels when most nitrogen is being applied as pre-plant fertilizer.

The final data from the overall study to be summarized in this report deal with lateral variations in soil dissolved inorganic N values. The first two sets of data in Table 7 involved experiments at the Othello station site, with alternate-furrow irrigation employed. The data compare values beneath crop rows with those from beneath irrigation furrows when using this irrigation system. Little difference between soil dissolved-N levels beneath rows and furrows were evident when this irrigation technique was practiced. The data also demonstrated that differences between the heads and tails of alternate-furrow-irrigated fields are normally more significant than differences between rows and furrows. They also show that the differences between rows and furrows were largely eliminated when subsoil values were dealt with under this type of irrigation practice.

A third set of data from the table deal with a comparison of extraction cup values for two sets of extraction cups located in the same set of

TABLE 6

Correlation of tuber yields with soil dissolved inorganic N or petiole nitrate-N values, 1973 and 1974.

Parameter	Location or Measure	*Total vs. soil N at:*				*No 1's vs petiole NO_3 at:*				*Total vs petiole NO_3 at:*			
		90	*104*	*118*	*132 days*	*90*	*104*	*118*	*132 days*	*90*	*104*	*118*	*132 days*
Average Linear Correlation Coefficients (1973)	Moses Lake	.68	.77	—	—	.02	.02	—	—	.01	-.06	—	—
	Othello	-.22	.07	.14	.06	.11	-.07	-.07	.09	.28	.16	-.16	.16
	Othello Station	.66	-.53	-.52	-.53	-.41	-.46	-.39	-.42	-.47	-.52	-.46	-.47
Tuber Yields (1974)		vs. petiole NO_3 at 90 days:				vs. petiole NO_3 at 150 days.				vs. petiole NO_3 at 120 days.			
		L1[a]	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4
	Total	584	695	718	642	775	761	843	797	700	682	655	725
	No 1's	424	509	507	476	550	494	611	481	503	480	496	516
Tuber Yields (1974) (related to entire season's petiole data)		vs. days petiole NO_3 < 10,000 ppm				vs. days petiole NO_3 < 5,000 ppm				vs. days petiole NO_3 < 7,500 ppm			
		0-20	21-40	41-60	61-80	0-20	21-40	41-60	61-80	0-20	21-40	41-60	61-80
	Total	727	707	723	757	718	644	771	899	722	751	671	791
	No 1's	480	523	513	537	524	457	547	656	498	556	483	570
Tuber Yields (1974) (related to petiole data to August 15)	Total	690	773	691	—	696	728	732	—	699	676	748	—
	No 1's	497	533	504	—	501	546	447	—	496	521	479	—

[a] L1 = < 8,000, < 4,000 and < 2,000 ppm at 90, 120 and 150 days, respectively;
L2 = 8,000 - 11,000, 4,000 - 8,000, and 2,000 - 4,000 ppm on the respective dates;
L3 = 11,000 - 14,000, 8,000 - 12,000, or 4,000 - 6,000 ppm; and
L4 = < 14,000, < 12,000 or < 6,000 ppm.

sprinkler-irrigated experimental plots at the Block 21 (sandy) experimental site. Each pair of extraction cups at a given depth were only a few feet apart, with both located beneath the crop row. As is evident from the data, large variations in dissolved-N levels at a given depth can be found within a few feet of lateral distance in the field. Such variations make reliance on data from a few sets of extraction cups highly questionable in terms of estimating field-wide leaching losses of nitrogen.

The final data of Table 7 provide a comparison of extraction cup data and soil sampling data from adjacent soils during three of the experimental study periods at the Block 21 and Othello Station experimental sites. Variations from one point in the field to another are evident from the data for the July or September sampling periods, when values for cups and for nearby soil were compared with one another. When the entire set of data for a given season were averaged, however, both soil sampling and extraction cups provided similar results. Thus, either method could be used to obtain reliable estimates of the amount of nitrogen being leached at a specific point in the field, and each technique serves as an independent confirmation of the experimental approach. Because of the greater versatility and increased numbers of areas that can be sampled with the soil sampling procedure, it is preferred over the extraction cup approach.

CONCLUSIONS

High levels of dissolved inorganic nitrogen commonly exist in soil solutions from within and beneath potato fields of the Columbia Basin area of Washington. A considerable potential for ground water and drainage water contamination by soil solutions displaced during excessive irrigation thus exists for this area. Careful sprinkler irrigation at quantities dictated by micrometeorological or pan evaporation data can produce near maximum yields of high quality tubers even on extremely sandy soils, while still maintaining residual dissolved-N from the current crop season in the top 60 to 120 cm of soil, where it can be removed by subsequent deep-rooted crops in the rotation. However, a common tendency to over-irrigate

TABLE 7

Average soil dissolved inorganic N values, including lateral variations.

Location	*Irrigation System*	*Depth*	*Average Dissolved N Values*[a]					
		(cm)	*(mg/liter)*					
Silt Loam Site (1972)	Alternate-furrow		Rows[b]			Furrows		
			Head	Tail	Sprikler[c]	Head	Tail	Sprinkler
		0-60	38	81	42	32	70	59
		60+	8	73	48	11	63	40
Silt Loam Site (1972)	Alternate-furrow		Overall[d]	Rows	Furrows			
		0-60	63	83	44			
		60+	52	61	50			
Sandy site (1972)	Sprinkler (high-rate)		First Extraction Cup[e]			Second Extraction Cup		
			July 8	Aug 12	Sept 9	July 8	Aug 12	Sept 9
		180	30	106	10	8	323	56
		240	41	70	94	42	41	46
Both Sites			Average for Cups			Average for Nearby Soil		
			July	Sept	Overall	July	Sept	Overall
	Sprinkler (1971)	—	122	94	103	148	74	106
	Furrow (1972)	—	71	42	56	74	48	57
	Furrow (1973)	—	242	—	225	336	—	209

[a] Soil sampling data, except where otherwise specified.
[b] Furrow-rate experiment, table 2.
[c] Long-term fertilizer factorial, table 2.
[d] 1972 suspension fertilizer experiment, table 2.
[e] Cups located a few feet apart, beneath the crop row, in the high-rate sprinkler plots of table 1.

late in the season, when plants have matured and crop water needs have diminished, must be curbed if the nitrogen is to be subsequently "scavenged" by future crops.

Increases in dissolved-N levels consistently were observed with increased fertilization rates, although the increases were not strictly proportional to fertilization rate. High levels of residual inorganic nitrogen persisted from fall until spring unless leached by over-winter rains. However, these levels were reduced to more acceptable values during a subsequent fallow period or following subsequent growth of a deep-rooted crop. Deep-leached nitrogen appeared to be neither assimilated nor denitrified to an appreciable extent, as evident from subsoil dissolved-N values for a long-term fertilizer experiment on a silt loam soil of the area.

Use of slow-release nitrogen fertilizers substantially lowered soil dissolved-N levels. The lower dissolved-N levels should have slightly lowered leaching losses during the growing season, although higher residual nitrogen levels often remained at season's end in plots fertilized with slow-release fertilizers. "Nitrogation" (sprinkler application of N fertilizers throughout the growing season) produced little evidence of substantial nitrogen leaching even at high fertilization rates and infrequent application intervals. However, soil dissolved-N levels of several tens of mg/l persisted even in nitrogated plots, because of the apparent inability of potatoes to efficiently utilize all nitrogen which may be present in the soil solution.

Fertilization rates of 250 to 350 kg of N per hectare were generally sufficient for maximum yield of high level tubers on recropped potato lands at the experimental locations sampled throughout the Columbia Basin. Overfertilization appears to be common in many portions of the Basin, and is poor practice from both an environmental and an economic viewpoint. No evidence of a "critical" plant petiole NO_3-N level was found for petiole NO_3-N levels above 5,000 ppm, even though a critical level of 10,000 ppm is commonly recommended in this area. This may account for some of the apparent excessive usage of nitrogen on potatoes in the Columbia Basin. Total yield or tuber quality was predictable from dissolved soil nitrogen or from petiole NO_3-N only for nitrogen-stressed (e.g. highly-leached) plots in our studies.

Ceramic extraction cups constituted a poor sampling procedure for dissolved soil nitrogen in these studies, due to extremes in concentrations which were encountered over lateral distances of only a few meters. The cups also failed to extract consistently from all depths at all times (producing variable sampling populations from one period to the next). There was also a high probability that solute peaks would be located between extraction cup depths on any given sampling date, and it proved hard to predict the exact effects of cup location with respect to fertilizer band location in band-fertilized fields. Extrapolation from a few extraction cup sites to an entire irrigated field appears to be an unreliable approach for monitoring or verifying fertilizer leaching patterns in most areas of the Columbia Basin.

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Variability of Nitrate Leaching Within Defined Management Units

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ABSTRACT

In attempting to relate nitrate concentrations below root zones to root zone soil characteristics, the experimental approach has consisted of a comparison of a number of sites within a defined management unit or field. The basic assumption in this approach has been that the management of the field is uniform and variations in nitrate leaching result from variations in soil characteristics. However, results reported herein show that even within a field of limited size, other sources and sinks can be significantly different at various sampling locations. The variation in these factors for a number of fields in the Santa Maria Valley, California is discussed.

INTRODUCTION

Increased interest over the past few years in groundwater degradation and stratospheric ozone destruction has led many scientists, politicians and control agency personnel to take an intensive look at agricultural uses of nitrogen fertilizers and their effects on the environment. In studying the fate of nitrogen applied to agricultural soils, a number of sources, sinks, and pathways need to be considered. The approach used most frequently in nitrogen studies has been to develop nitrogen balances that consider various sources and sinks. An example of this type of study was recently reported by Fried, et al. (1976). In this simplified model, a steady state is assumed in which the inputs of nitrogen are equal to the outputs. The sinks of nitrogen described by this model that are of most interest at the present time are nitrogen losses by leaching and dentrification. Nitrates that leach below the root zone are considered those that are beyond recovery of plants. One of the products of denitrification is nitrous oxide, which may have far-reaching implications with regard to depletion of stratospheric ozone.

In developing nitrogen balances to consider the magnitude of various sinks, areas of various size can be considered, including drainage basins (Ayers and Branson, 1973) or individual field plots (Adriano, 1972). However, defined management units (farmers' fields) will probably be the most important in determining amounts of nitrogen leached or dentrified, or in attempting to change the magnitude of these sinks. In determining nitrate concentrations below root zones and nitrogen balances for defined management units, hereafter called field, it is necessary that one understands the variability likely to be encountered. By understanding the contributions of various factors to this variability, sampling and analysis programs can be designed that will increase the reliability of data.

As described by numerous authors, including Fried, et al. (1976), a steady state model for nitrogen can be described by the equation

$$N_F + N_I + N_M - C - L - DN - P = O \qquad [1]$$

where N_F is the nitrogen added in fertilizers, N_I is the nitrogen added in the irrigation water, N_M is the nitrogen added by miscellaneous ways including NH_3 adsorption, rainfall, etc., C is the nitrogen removed in the harvested crop, L is the nitrogen leached below the root zone, DN is the nitrogen lost of denitrification, and P is miscellaneous losses due to erosion, runoff, NH_3 volatilization, etc. At steady state the assumption is that there is no net change in the soil nitrogen pool over the time studied. Since at this time it is very difficult and/ or expensive to measure DN directly in the field, this equation is generally rewritten as

$$DN = N_F + N_I + N_M - C - L - P \qquad [2]$$

In attempting to relate nitrate concentrations below root zones to soil characteristics

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of the root zones, the experimental approach has consisted of a comparison of a number of sites within a defined management unit or field. The basic assumption in this approach has been that the management of the field is uniform and variations in nitrate leaching (L) result from variations in soil characteristics. However, we have found that even within a field of limited size, the other sources and sinks in equation [2] can be significantly different at various sampling locations. The variation in these factors for a number of fields in the Santa Maria Valley, California is discussed in this paper.

TABLE 1.

Particle Size Distribution and Organic Carbon Content of Surface Horizon for Eight Sites Within a Defined Management Unit

Site	*Sand*	*Silt*	*Clay*	*Organic Carbon*	*Color*
			%		
343	61.0	32.1	6.9	.39	10YR3/4
344	60.7	32.3	7.1	.49	10 YR3/4
345	59.9	33.0	7.1	.43	10YR3/4
346	61.2	31.9	6.9	.25	7.5YR4/4
347	53.9	33.1	13.0	.17	7.5YR4/4
348	58.4	34.5	7.0	.44	10YR3/3
349	67.6	26.3	6.1	.47	10YR3/3
350	57.4	33.6	9.0	.16	7.5YR5/6

MATERIALS AND METHODS

Fields that have a variety of soil profiles were selected as study areas for determining nitrogen balances, nitrate concentrations below root zones for typical management systems, and the magnitude of denitrification losses. Eight or nine sites were sampled in each field that is described here. The soil profile to 6 feet at each site was described, sampled and characterized. Soil samples were collected from three holes at each site in 1-foot increments between 6 and 20 feet. The lower depth was less in cases where obstructions or perched water tables were encountered while drilling with a Giddings hydraulic auger. Chloride concentrations were determined for saturation extracts by automatic titration and expressed on a soil solution basis by using field moisture contents of the soils. Soil solution chloride values reported here represent means of 12 to 42 samples. Particle size analyses were done by the pipette method (Day, 1965) and organic carbons were determined by wet oxidation (Allison, 1965).

Yields were determined by sampling from a 10 x 10 m plot at each site at harvest time. Three yield determinations were made within each plot and crop samples from each yield test were analyzed for total nitrogen (semimicro-kjeldahl) and chloride (Adriano, et al. 1973).

RESULTS AND DISCUSSION

Field Characteristics

A number of characteristics of a field have important effects on the variable in equation [2], some of which will be discussed later. However, one of these characteristcs that is very important and needs to be considered is the complex of soils present in the field. Soils can be described or considered in many ways. Examples would be soil mapping units, or soil pedons present, or the variation in surface or subsoil textures. In few instances does one find fields that have only one mapping unit. By examining a soil map of an area, for example, western Riverside County, California, it is evident that most fields have at least several mapping units. In addition, mapping units on a detailed soil map have only a certain degree of uniformity. Thus, the variation in soil characteristics present in most fields necessitates sampling more than one site within a field to develop a nitrogen balance. Pratt, et al. (1977), discussed the number of cores needed per field to adequately represent the field for a variety of situations in California.

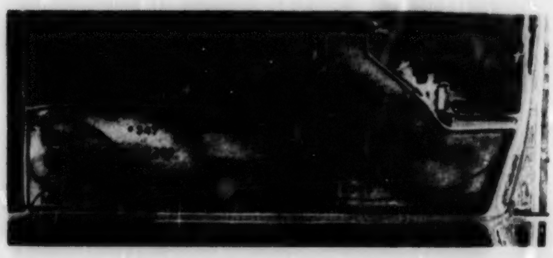

Figure 1. Field in Santa Maria Valley studied for nitrogen balance. Mapping units are MaA-Marina sand, 0 to 2% slopes; MaC-Marina sand, 2 to 9% slopes; PnA-Pleasanton sandy loam, 0 to 2% slopes; and PnC-Pleasanton sandy loam, 2 to 9% slopes. Location of sites sampled are indicated by dots.

Three fields in the Santa Maria Valley, California which are presently being studied to

develop nitrogen balances are shown in Figures 1 and 2. Soil boundaries as taken from the Northern Santa Barbara County Soil Survey Report (Shipman, 1972) are shown on the figures along with the locations of sites that have been sampled. The varying shades of gray on Figure 1 are due to soil variation. This is supported by particle size and organic carbon data for surface horizons of the various sites (Table 1). No obvious color patterns due to soil variation are present in Figure 2. However, data given in Table 2 show distinct particle size and organic carbon differences between sites. Also, these variations are not reflected in the soil mapping units and thus care must be exercised even when using soil maps to ensure that all soil bodies within the field are sampled.

Other field characteristics that need to be considered in certain instances include surface configuration, depth to water table, and irrigation system layout, as discussed later.

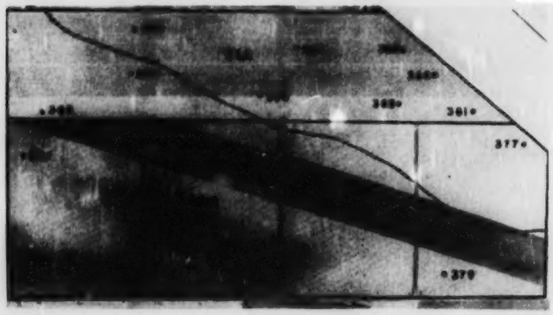

Figure 2. Two fields in Santa Maria Valley studied for nitrogen balances. Mapping units are StA-Sorrento sandy loam, 0 to 2% slopes and SuA-Sorrento sandy loam, sandy sub-stratum, 0 to 2% slopes. Fields boundaries are shown by dark straight lines.

Nitrogen Inputs

Fertilizers (N_F): The amount of nitrogen added per unit area is one of the input values needed for a nitrogen balance for a field. When considering the field as a whole, one needs only to determine the total amount of fertilizer applied and the total area to calculate N_F. However, the distribution of that total nitrogen applied becomes important when a specific site within a field is sampled. The uniformity of yields and nitrogen available for leaching will depend on the distribution.

One of the obvious factors that will affect the uniformity of distribution is the method of application. Methods such as banding or side-dressing will result in more uniform application along rows than across rows. Uniformity of application by broadcasting with a gravity spreader will depend largely on the operator. A bulk spreader equipped with a centrifugal spreader will give nonuniformity (Brinsfield and Hummel, 1975; Cunningham, 1963). When nitrogen is added in irrigation water, the uniformity of water application in the field becomes important as does runoff of irrigation water. These points will be discussed later.

TABLE 2

Particle Size Distribution and Organic Carbon Content of Surface Horizon for Seventeen Sites Within a Defined Management Unit.

Site	*Sand*	*Silt*	*Clay*	*Organic Carbon*	*Color*
			%		
360	73.6	18.8	7.6	.31	10YR4/4
361	74.7	17.6	7.7	.33	10YR4/4
362	73.9	18.2	7.9	.35	10YR4/4
363	67.2	22.3	10.4	.40	10YR3/3
364	63.9	25.1	11.0	.43	10YR3/3
365	71.3	20.4	8.3	.30	10YR3/3
366	74.0	18.4	7.7	.34	10YR3/3
367	65.4	24.8	9.8	.42	10YR3/3
368	52.3	34.0	13.7	.58	10YR3/3
369	54.1	34.0	11.8	.58	10YR3/3
370	66.7	22.3	11.0	.38	10YR4/2
371	55.2	30.5	14.3	.60	10YR3/3
372	55.5	31.5	13.1	.64	10YR3/3
373	70.5	20.3	9.2	.34	10YR3/3
374	61.5	26.2	12.3	.51	10YR3/3
375	68.3	22.0	9.7	.44	10YR3/3
376	79.7	14.2	6.2	.30	10YR3/3

Irrigation Water (N_I): Many waters used for irrigation contain significant amounts of nitrogen, usually as nitrate. This source of nitrogen needs to be considered in developing nitrogen balances and again the uniformity of water application will determine the uniformity of nitrogen applied in the irrigation water. As an example of the magnitude of nitrogen added by the irrigation water, water used to irrigate crops in the Santa Maria Valley typically contains 10 ppm NO_3-N. If 60 ha-cm of water is applied to a crop, 60 kg of nitrogen would be added per hectare. If one is growing vegetables where 224 kg of fertilizer nitrogen are added per hectare, this 60 kg would account for only 20% of the input; but, on lima beans where a typical fertilizer rate is 56 kg/ha, the irrigation water would account for over 50% of the nitrogen input.

Miscellaneous (N_M): Some miscellaneous inputs of nitrogen would be soil or plant adsorption of NH_3 from the atmosphere, nitrogen in rainfall, and fixation of atmospheric nitrogen. Adsorption of NH_3 by soils has been discussed by Malo and Purvis (1964), Hanawalt (1969), and Luebs, et al. (1973). If fields of interest are near feedlots or dairies, then contributions of atmospheric NH_3 need to be considered. Rainfall is generally considered to contribute 5 to 7 kg of N per hectare per year. Again for most intensive farming, this amount is negligible. Most nitrogen balance studies are conducted for non-nitrogen-fixing crops. If nitrogen-fixing crops are studied, nitrogen inputs from this source need to be included.

TABLE 4

Yields, Nitrogen Contents of Peppers and Amounts of Nitrogen and Chloride Removed in the Harvested Crop for Nine Sites Within a Defined Management Unit (Figure 2).

Site	*Yield*	*N content*	*N removed+*	*Cl removed+*
	metric T/ha	%	kg/ha	kg/ha
360	12.72	2.45	91 bc	18 bc
361	12.41	2.42	88 bc	17 c
362	16.96	2.39	118 abc	25 bc
363	27.01	2.25	176 a	53 a
364	26.72	2.09	163 ab	42 ab
365	18.91	1.96	108 abc	40 ab
366	17.12	2.14	107 abc	26 bc
367	10.75	2.47	77 c	8 c
368	12.74	2.44	91 bc	9 c
Mean	17.25	2.29	113	27

+Values followed by the same letter are not significantly different at the 1% level.

Nitrogen Outputs

Harvested Crop (C): Nitrogen is applied to agricultural lands to satisfy the requirements of the growing vegetation. Many researchers have shown that the use efficiency of applied nitrogen is considerably less than 100%. Thus, some of the applied nitrogen is lost to other sinks. In determining the amounts of nitrogen removed in the harvested crop, it is necessary to understand various production systems. For example, in dry lima bean production, the only material that leaves the field, unless the straw is used for bedding or feed, is the dry beans. In the case of cauliflower, part of the vegetative portion is used to protect the head, thus more nitrogen is removed from the field than just that in the head.

When determining the nitrogen removed by the harvested crop, the variation at different sites within the field must be considered. In working with nitrogen balances for fields in the Santa Maria Valley, California, we have experienced this variability. Data on yields and nitrogen removals for three crops from the fields shown in Figures 1 and 2 are given in Tables 3,

TABLE 3

Yields, Nitrogen Content of Sugar Beets and Amounts of Nitrogen and Chloride Removed in the Harvested Crop for Eight Sites Within a Defined Management Unit (Figure 1).

Site	*Yield*	*N content*	*N removed+*	*Cl removed+*
	metric T/ha	%	kg/ha	kg/ha
343	56.74	1.13	94 d	93 c
344	94.57	1.00	179 a	45 d
345	92.93	1.39	181 a	96 c
346	87.10	1.12	149 b	98 c
347	88.38	.71	116 cd	39 d
348	91.47	1.39	190 a	145 b
349	94.01	.89	137 bc	157 b
350	86.09	.59	91 d	201 a
Mean	86.40	1.03	142	109

+Values followed by the same letter are not significantly different at the 1% level.

TABLE 5

Yields, Nitrogen Contents of Dry Lima Beans and Amounts of Nitrogen and Chloride Removed in the Harvested Crop for Eight Sites Within a Defined Management Unit (Figure 2).

Site	*Yield*	*N content*	*N removed+*	*Cl removed+*
	kg/ha	%	kg/ha	kg/ha
370	2332	4.13	91 ab	1.5 b
371	2324	4.46	98 ab	1.8 b
372	2180	4.53	93 ab	1.7 b
373	2002	3.76	71 c	1.5 b
374	2747	3.55	91 c	2.4 a
375	2978	3.65	102 a	2.2 a
376	2573	3.39	82 bc	2.2 a
377	1692	3.15	50 d	1.0 c
Mean	2354	3.83	84	1.8

+Values followed by the same letter are not significantly different at the 1% level.

4, and 5. The yields of sugar beets at eight locations within a 14-ha field varied from 57 to 94 metric T/ha (Table 3). The amounts of nitrogen removed in the harvested crop ranged from 91 to 190 kg/ha with an average of 142 kg/ha. Yields of peppers grown on a 24-ha field ranged from 11 to 27 metric T/ha for nine locations (Table 4). Nitrogen removed from the field varied from 88 to 176 kg/ha with an average of 113 kg/ha. The amount of nitrogen removed by dry lima beans was lower than either sugar beets or peppers (Table 5). Fifty to 102 kg/ha of nitrogen were removed from eight locations within a 49-ha field. The average nitrogen removed was 84 kg/ha for eight sites where the yield from 1692 to 2978 kg/ha. From these data it is apparent that there are not only marked differences in nitrogen removal by various crops, but there can also be significant differences between locations within a field with "uniform management."

Leaching losses (L): In determining the amounts of nitrogen leaching below root zones, it is necessary to know the amount of water leaching from the root zone (drainage volume) and the concentration of nitrogen, generally NO_3-N, in that water. Two ways of determining the drainage volume are (1) by using a value for evapotranspiration (ET) in relation to the amount of water applied, and (2) by using an estimation of the leaching fraction as a portion of the water applied. In most cases in California, adequate ET data are lacking so the second method is more generally used. The drainage volume by this method is calculated as

$$D = IW_{app}\,LF \qquad [3]$$

where D is the drainage volume expressed as surface cm, IW_{app} is the volume of water applied expressed as surface cm and LF is the proportion of applied water moving below the root zone. The LF can be approximated by

$$LF = Cl_I / Cl_D \qquad [4]$$

where Cl_I is the choloride concentration in the irrigation water corrected for fertilizer inputs and crop removals and Cl_D is the chloride concentration in the drainage water. This technique for determining LF has been discussed previously by Pratt, et al. (1972, 1977). By combining equations [3] and [4] the drainage volume can be calculated as

$$D = IW_{app} \frac{Cl_I}{Cl_D} \qquad [5]$$

In using this equation one must have reliable data on the water inputs and chloride concentrations in applied water, fertilizer, harvested crop, and drainage water.

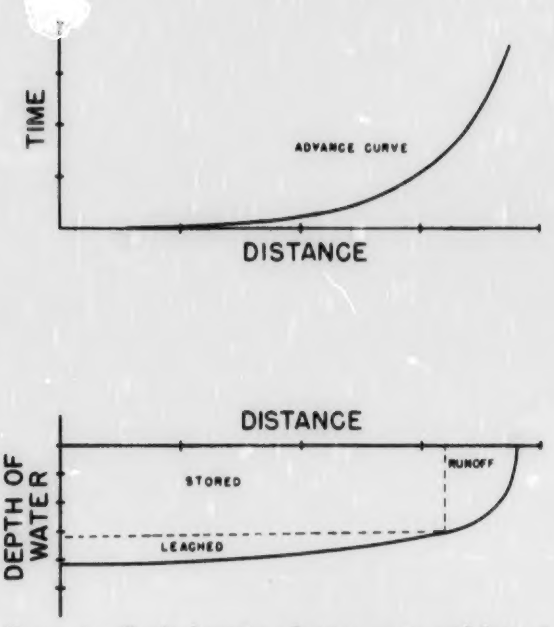

Figure 3. Typical water advance curve and fate of applied water for furrow irrigation. The dashed line indicates the root zone.

First, let's consider the application of water to a field of interest. If received as rainfall, the distribution over most fields will be uniform except where runoff occurs due either to slope or to rainfall intensity. But for most situations, especially in the arid west, the rainfall can be ignored and the uniformity of irrigation water appliction is much more important. Sprinkler and furrow irrigation are used for most field and vegetable crops in California and they will be considered here. Drip irrigation by which water is applied at specific points is being used extensively on tree crops but will not be considered here.

The uniformity of application of water by sprinklers has been discussed by numerous authors (Christiansen, 1942; Criddle, 1965; Chaudhry, 1976). Factors that affect the uniformity of application include system layout, wind patterns, and surface configuration. In field crops where a sprinkler system is not permanent and surface gradients are very small, it is very difficult to generalize as to specific parts of a field that may receive more water than another part. When considering a steady state system, where the management has been relatively uniform over a period of years, it may be reasonable to assume that the variations in application will even out over time (Kruse, et al. 1962).

A quite different situation exists in the case of furrow irrigation. With furrow irrigation, water is always applied in the same direction and this has implications relative to uniformity of application. Figure 3 shows a generalized example of water applied during furrow irrigation in relation to distance from the source of water (Willardson and Bishop, 1967: Merriam, 1969). In this example, it is assumed that the soils are uniform throughout the length of the furrow. As shown, more water is applied at the upper end of the field than at the lower end. This amount is increased with decreased efficiency of the irrigation system. Thus, with furrow irrigation there is a built-in "nonuniformity" as it applies to water application. This nonuniformity should be more predictable for a field with uniform soils than for one with a wide variety of soils. In comparing furrow and sprinkler irrigation, Kruse, et al. (1962) found that 28% less water was added to the root zone of the downstream 1/4 of sorghum plots than to the upstream 1/4. Water distribution variations occurred more at random on the sprinkled plots.

If one considers the effects of furrow irrigation on drainage volumes at various sites within a field, possibly some of the variation in D can be anticipated. From equation [4] as the LF decreases, the chloride concentration in the drainage water will increase with the constant chloride input. From Figure 3, it is evident that for furrow irrigation the LF would decrease with the distance from the water source. This has been the case for several sites that we have investigated in the Santa Maria Valley. The relationship between Cl_D and distance from the water source is shown for three fields in Figures 4 and 5. The fields represented in Figure 4 are furrow irrigated, while the field represented by Figure 5 is sprinkler irrigated. For the furrow irrigated fields where the soils are reasonably uniform sandy loams, there is a significant increase in Dl_D as the distance from water source increases. For the sprinkler irrigated field, a relation between Dl_D and distance would not be expected and that is the case for the field shown in Figure 5.

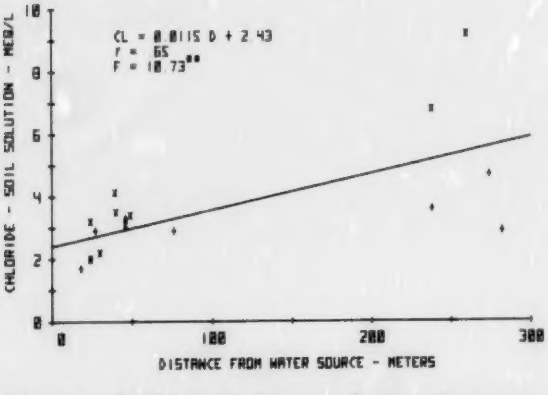

Figure 4. Relationship between distance from water source and chloride concentrations in the soil solution below root zone of fields shown in Fig. 2. These fields are furrow irrigated.

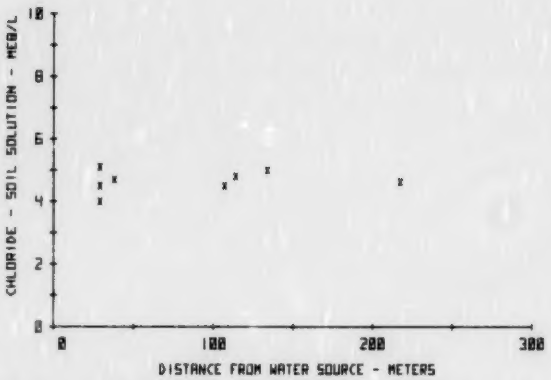

Figure 5. Relationship between distance from water source and chloride concentrations in the soil solution below root zone of a sprinkler irrigated field. Distances measured from point where water would be applied if furrow irrigated.

Another point to consider in relation to calculating drainage volumes from equation [5] is that Cl_I the choloride concentration in the irrigation water, needs to be adjusted for other inputs of chloride such as in fertilizers or organic amendments and losses in the harvested crop. For example, if KCl is added as a fertilizer or manure is spread on the field these inputs need to be considered. In our studies in the Santa Maria Valley, we have also found that some crops remove significant amounts of chloride. Depending on the amount of salt added in the irrigation water relative to that removed by the crop, the error in calculating D by equation [5] can be quite large if the crop removal of chloride is ignored. The % error can be expressed as

$$\% \text{ Error} = \frac{D_o - D_c}{C_c} \times 100 \qquad [6]$$

where D_o is the calculated drainage volume assuming no crop removal of chloride and D_c is the calculated drainage volume after making the appropriate correction for crop removal of chloride. By appropriate substitution this equation becomes

$$\% \text{ Error} = \frac{C_r}{Cl_I VK - C_r} \times 100 \qquad [7]$$

where C_r is the amount of chloride removed per unit area, Cl_I is the chloride concentration in the irrigation water and V is amount of water applied in ha-cm and K is the conversion factor to convert chloride concentration to an amount per unit area. Plots of this equation for typical water application rates and chloride concentrations are shown in Figure 6. In considering this figure in connection with typical crop removal of chloride for various crops (Table 6), one can see that in many cases the crop removal cannot be ignored. For example, if 60 ha-cm of water (1.5 meq Cl/1) were applied to sugar beets, the drainage volume would be overestimated by 53% if the crop removal of 112 kg/ha was not considered.

Like nitrogen removals that were discussed previously, chloride removals can be quite variable at different locations within a field. Significant differences were found between sites within the three fields discussed previously (Tables 3, 4, and 5). These data also demonstrate the large differences between crops.

The points discussed here show that many factors need to be considered when using equation [5] to calculate drainage volumes. Some of these are apparent but others are more obscure.

TABLE 6

Amounts of Chloride Removed by Various Crops in Santa Maria Valley.

Crop	*Chloride*	*Yield*	*Chloride removed*	Cl_I
	%	metric T/ha+	kg/ha	mg/1
Artichokes	1.10	7.4 e	13	1.6
Broccoli	.66	7.8 e	7	1.6
Cauliflower	.34	11.2 e	4	1.3
Celery	3.20	67.0 e	129	4.8
Lettuce	2.48	56.0 m	34	4.8
Lima Beans	.08	2.4 m	2	1.4
Peppers	.49	18.6 m	28	1.3
Potatoes	.36	40.7 m	26	1.6
Sugar Beets	.81	86.3 m	110	2.3

+e—yield was estimated
m—yield was measured

Physical losses (P): As with the miscellaneous additions of nitrogen, the miscellaneous losses are important only in specific cases. If nitrogen is applied as NH_3, then volatilization needs to be considered. When nitrogen is applied in the irrigation water, nitrogen lost in runoff must be taken into account. Losses by erosion may occur where steep surface gradients exist but generally they can be ignored.

Dentrification (DN): Data obtained directly for loss of nitrogen by denitrification for field situations are generally lacking. Most denitrification values assigned to soils, management or crop factors are obtained by difference (equation [2]). Thus, the variability of other factors (L, C, etc.) will affect the magnitude of DN. Presently, extensive research is being conducted to determine the relationships between denitrification levels and soil and management factors. With the use of isotopes of nitrogen and field gas measurements, data should be available in the near future on the variability of DN within fields. These data will also enable one to check the "balance" of nitrogen within a system and none of the factors will have to be calculated by difference.

Implications

What does this research indicate relative to irrigation return flow quality management? One of the main implications of the research reported here, along with previous work completed on our nitrate project, is that the use of soil sampling to monitor nitrate concentrations leaching below root zones is probably cost-prohibitive. To obtain reliable data for nitrates leaching below root zones, the variability of the factors controlling the pool of nitrogen available for leaching must be taken into consideration when designing a sampling program. As pointed out in this paper, crop removal of nitrogen will vary over a field. Sampling must include sites where crops have removed large amounts of nitrogen and where crops have removed small amounts. Only by studies preliminary to a monitoring program can these locations be identified.

Type of irrigation systems will also influence the design of a sampling program. A stratified design may be necessary for furrow or border irrigation systems while a random design may be satisfactory for fields irrigated by sprinklers. Analysis of our data along with literature relative to irrigation systems would indicate that when sampling fields irrigated by furrow or border methods, sites in close proximity to the water source should be sampled along with positions at greater distances from the water source. This is because of the lesser quantities of water applied at the lower end of fields irrigated by these methods.

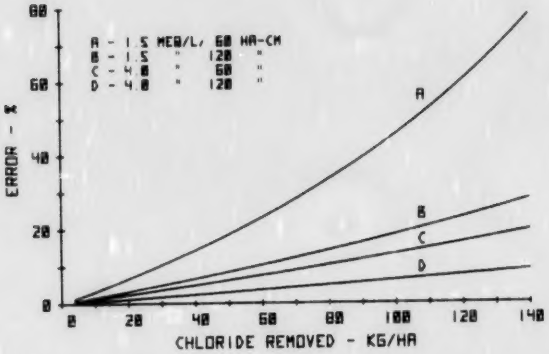

Figure 6. Relationship between chloride removed by harvested crop and % error in drainage volume if Cl_I is not corrected for crop removal of chloride.

Soil variation also needs to be taken into account when sampling. The effects of soil characteristics on plant growth, water transmission and retention characteristics and denitrifiction potential will all be important in determining the magnitude of the nitrogen pool available for leaching. Even within a single mapping unit, considerable variation exists and one sample from the center of a soil body will not adequately represent that mapping unit. Also, soil properties traditionally used for mapping soils are only indirectly related to water transmission characteristics. These characteristics are very important in relation to water application vs. field position, period of saturation following irrigation, and leaching volumes. Sampling programs must include these variations.

After all of these variations are considered when designing a soil sampling program, one often finds that a very intensive sampling program is necessary. Data presented by Pratt, et al. (1977) for 4 fields (25-90 ha) in Ventura, Kern, and Madera Counties, showed that 5 to 21 sites were needed (8 samples with depth per site) to obtain measured mean nitrate concentrations that would fall within 30% of the true mean at the 95% confidence level. To be within 10% of the true mean it would have been necessary to sample 23 to 161 sites per field. Only by preliminary studies can these numbers be determined. However, they can be anticipated to some extent by considering the factors discussed in this paper.

Monitoring nitrate leaching by soil sampling does not appear to be feasible for basin-wide studies. As a research tool to study the components of the nitrogen cycle it has proved useful, but we would not recommend it as a monitoring method. A more positive aspect of this research has been the accumulation of data showing the amounts of nitrate that have leached from root zones and an improved understanding of the nitrogen cycle and factors that affect the pathways between various sources and sinks. For improved nitrogen management and thereby improved return flow quality, the magnitude of the nitrogen pool available for leaching must be minimized. This can be done by increasing crop uptake efficiency of applied fertilizers, lower fertilizer application rates and/or increased denitrification of excess nitrogen. Through present and future research these points will be more fully elucidated and "ideally" better nitrogen management will result.

ACKNOWLEDGMENTS

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Field Measured Flux of Volatile Denitrification Products as Influenced by Soil-Water Content and Organic Carbon Source

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ABSTRACT

The amount of NO_3^- in irrigation return flow waters is dependent upon each of the components of the N cycle in soils. One of those components for which absolute amounts and rates are not well known is denitrification. Volatile denitrification products, primarily N_2O and N_2, are evolved whenever anoxic sites develop within the soil and when sufficient carbon is available. Absolute amounts and rates of denitrification from a Yolo loam field profile at Davis, California, were studied in relation to the influence of soil-water content and organic carbon source. Field plots were intensely instrumented with soil atmosphere samplers, soil solution samplers, and tensiometers. Soil-water pressure heads (h) in the upper 15 cm of soil were maintained constant at -15 and -70 cm of water. Three levels of soil carbon were evaluated from plots cropped with ryegrass, uncropped plots, and plots to which manure was mixed in the top 10 cm of soil. Fertilizer was applied at the rate of 300 kg N ha^{-1} as KNO_3 enriched with 20 and 40% ^{15}N for the h= -15 and h= -70 cm treatments, respectively. The flux of volatile gases at the soil surface was measured from the accumulation of N_2O and $^{15}N_2$ beneath an air-tight cover placed over the soil surface for 1 or 2 hours per day. Denitrification occurred in order of decreasing magnitude in manure (h = -15 cm), manure (h = -70 cm), uncropped (h = -15 cm), and uncropped (h = -70 cm) plots. Approximately 70% of the fertilizer nitrogen was denitrified for the manure (h = -15 cm) treatment. Approximately 1 % of the added fertilizer was denitrified in the uncropped (h = -70 cm) treatment.

INTRODUCTION

The amount of NO_3^- reaching the ground water of irrigated lands is dependent upon each of the components of the N cycle in soils. The amount of fertilizer N applied and crop uptake of N are easily measured parameters of the total balance. The other components of the N balance, however, are not as easily measured or determined. The other components of the N balance has been a subject of much study and is the primary concern in terms of NO_3^- in ground water. The natural spatial variability of the leaching component has been demonstrated to be large (Biggar and Nielsen, 1976). The other components such as residual soil N, denitrification, and NH_3 volatilization losses are also not easily measured. The residual soil N is difficult to measure due to the large organic N pool of most soils and complicated by the natural spatial variablily of that pool (Rolston, 1977). The transient processes of immobilization and mineralization within the large organic N pool also contribute to the complexity of the measurement. Volatilization loss of fertilizer as NH_3 occurs to varying degrees in calcareous soils. This component can generally be minimized by incorporating NH_4^+ fertilizer below the soil surface. Another loss of N from the soil system for which absolute amounts and rates are not well known is denitrification. Volatile denitrification products, primarily N_2O and N_2, are evolved whenever anoxic sites develop within the soil and when sufficient carbon as

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supplied by soil organic matter, plant materials, and manure is available.

Simulation models of the N balance in soil systems attempt to predict the amount and concentration of NO_3^- in irrigation return flow water as a function of irrigation and cropping practices (Mehran and Tanji, 1974; Donigan and Crawford, 1976; Shaffer et al., 1976; Tanji and Gupta, 1977; and van Veen, 1977). In general, the denitrification component of the various mathematical models has not had adequate input data especially for the rates of denitrification. Total denitrification of applied fertilizer is used quite frequently such as 10-15% of the fertilizer N applied (Fried et al., 1976).

Very few experiments have evaluated the absolute amounts and rates of denitrification in the field. Rolston et al. (1976) demonstrated that the volatile gases from denitrification could be measured in a field profile. Total denitrification from gas fluxes compared reasonably with denitrification determined by difference for a small, intensely-instrumented, field plot. Total denitrification was determined by integrating with time the flux of the gaseous denitrification products as determined from measured soil gaseous diffusion coefficients and concentration gradients. However, these studies only evaluated the amount of denitrification under one cropping or carbon input system and one soil-water content near saturation. The objectives of this paper were to measure the absolute amounts and rates of denitrification from a field profile at Davis, California, as influenced by soil-water content and organic carbon source.

MATERIALS AND METHODS

The field plots were located on Yolo loam soil (Typic Xerorthents). The average soil temperature at the 5-cm depth was 23°C during the experimental period. Six 1-m^2 plots were established with a 60-cm deep redwood barrier around each undisturbed block of soil. Three plots were constantly maintained at a soil-water pressure head (h) of -15 cm and three plots were maintained at -70 cm of water. In order to establish different carbon treatments within each of the two water regimes, two plots were cropped with perennial ryegrass (Lolium perenne) for approximately 4 months prior to the experiment, two plots remained uncropped, and manure was mixed in the top 10 cm of soil of two plots approximately 2 weeks before fertilizer was applied. Each of the six plots were instrumented with tensiometers, soil solution samplers, soil atmosphere samplers, and thermocouples. Five soil atmosphere samplers were installed at the 2-, 5-, 10-, and 15-cm depths. Three soil atmosphere samplers were installed at the 20-, 30-, 60-, 90- and 120-cm soil depths. Triplicate samplers, designed to function as a tensiometer or solution extractor, were installed at the 60-, 90-, 120-, 150- and 180-cm depths of the soil profile. Triplicate tensiometers were also installed at the 5- and 15-cm depths. Duplicate thermocouples were installed at the 5-cm depth. Soil solution samplers consisted of porous cups glued to polyvinyl chloride tubing. Soil solution samples were obtained by evacuating bottles connected to the samplers. Soil atmosphere samplers consisted of 0.1-cm inside diameter nylon tubing glued into a 5-cm long, perforated, acrylic plastic tube. For the deeper soil depths, the small diameter nylon tubing was placed inside a 1.3-cm diameter polyvinyl chloride tube and the nylon tubing glued into a milled plastic tip. For all samplers, the volume of the sampling tubes was very small. Soil atmosphere samples were taken in 1 ml increments and N_2O, CO_2, O_2, and N_2 analyzed by gas chromatography. Another 0.5 to 1.0 ml of gas was taken to determine $^{15}N_2$ with a mass spectrometer. All gas samples to be analyzed by mass spectrometry were pulled through ascarite, dehydrite ($Mg(ClO_4)_2$), and a commercial O_2 scrubber.

Nitrate solution equivalent to 300 kg N ha^{-1} was uniformly applied to the plots by applying approximately 3 ml of solution to each of 400 points at the soil surface. The ^{15}N enrichment was 20 and 40% excess for the h = -15 cm and h = -70 cm treatments, respectively.

Within 6 hours after applying the fertilizer solution, an air-tight cover was placed over the plots. Samples of the atmosphere beneath the cover were taken after 1 or 2 hours for $^{15}N_2$ and $^{15}N_2O$ determinations. Soil atmosphere samples from within the soil profile were also taken soon after applying the fertilizer. Both soil profile samples and samples from beneath the cover were taken daily for a few days after the fertilizer was applied and then at less frequent intervals unitl $^{15}N_2$ and $^{15}N_2O$ could no longer be detected above background.

Soil solution samples were taken at weekly intervals. The grass of the cropped plots was cut periodically and the total clippings dried for analysis.

RESULTS

Concentrations of $^{15}N_2$ gas from denitrification of the added fertilizer as a function of soil depth at 2 days after fertilizer application for the plots of the h = -15 cm treatments are given by Fig. 1. The concentration profiles demonstrate the enormous differences in N_2 production among the cropped, manure, and uncropped plots. The differences in anoxic development were also evident from differences in concentration of 0_2 within the plots. For the cropped and manure plot, the minimum 0_2 concentration was 9.0 and 2.7% at the 20- and 10- cm depths, respectively. Concentration of O_2 within the uncropped plots became no smaller than approximately 15%. It appears from Fig. 1 that the greatest denitrification in the manure plot was occurring in the upper 10 cm of soil, whereas denitrification in the cropped plot appeared to be occurring slightly deeper. Similar data for the plots of the h = -70 cm treatment for 2 days after application of fertilizer are shown by Fig. 2. There was much less production of N_2 in the h = -70 cm treatments than in the h = -15 cm treatments. Oxygen concentrations in the cropped, manure, and uncropped plots became no smaller than 17, 15, and 17%, respectively. Similar concentration profiles were measured for N_2O. Since N_2O concentrations did not become great enough to measure ^{15}N without concentrating the N_2O sample, N_2O concentrations greater than initial values were considered to be derived from the fertilizer.

Total flux of the gaseous denitrification products ($N_2 + N_2O$) derived from the fertilizer as a function of time for the two manure plots are given by Fig. 3. These fluxes were determined from the accumulation of $^{15}N_2$ and N_2O beneath a cover placed over the soil surface for 1- or 2-hour intervals. The numbers below each of the soil-water pressure head treatments are total denitrification as determined from the area beneath each of the flux versus time curves. The flux calculated from the concentration increase beneath the cover was corrected for the decrease in the concentration gradient with time as the gases accumulated. The decrease in the concentration gradient with time would result in an underestimation of the diffusive flux as measured from concentration changes beneath the cover. A simple correction for this underestimation of the flux can be made based upon the steady-state diffusion equation,

$$f = -D_p\,(dC/dx) \qquad [1]$$

where f is the gaseous flux, D_p is the soil gaseous diffusion coefficient, C is gas concentration, and x is soil depth. If it is assumed that the concentration at the soil surface is equal to the concentration beneath the cover and that the concentration at the shallowest sampling depth (2 cm) does not change with time, the following boundary conditions apply:

$$C = C_o \quad , \quad x = 0 \text{ cm} \qquad [2a]$$
$$C = C_2 \quad , \quad x = 2 \text{ cm} \qquad [2b]$$

The solution to Eq. [1] and [2] rearranged to solve for D_p is

$$D_p = -(VL)\,/\,(At)\ln\left[(C_2 - C_o)\,/\,C_2\right] \qquad [3]$$

where V is the volume of the chamber placed over the soil surface, L is the depth of soil for which measurements are taken (2 cm), A is the cross-sectional area of the soil covered with the chamber, t is the time after covering the soil at which the concentration beneath the lid (C_o) was measured, and ln is the natural logarithm. The value of D_p was determined from Eq. [3] for the 0 to 2-cm depth interval from the change in concentration (C_o) of $^{15}N_2$ and N_2O over a 1- or 2-hour time period and the measured concentration at the 2-cm depth (C_2). The calculated D_p and the measured concentration gradient (dC/dx) at t = 0 (assumed to be linear for 0 to 2 cm) were used to calculate the corrected flux from Eq. [1]. This corrected flux was the best estimate of the gaseous flux of $^{15}N_2$ and N_2O if the cover had not been placed over the soil surface. Measurements of concentration at the 2-cm depth both before and after the cover had been in place for 2 hours demonstrated that Condition [2b] was valid for a 2-hour period. The greatest correction in the calculated flux was for the cropped (h = -15 cm) treatment with 6 kg N ha^{-1}. Corrections for all other plots were less than 5% of the total denitrified.

The increase in the flux at 1.4 days of the h = -15 cm treatment (Fig. 3) was from a sample taken in the afternoon of a fairly hot day. Thus, the fluxes may be slightly underestimated for a few days after application due to increased denitrification as surface soil temperature increased in the afternoon.

Similar data for the flux of N_2 and N_2O from the fertilizer as a function of time for the cropped and uncropped plots are given by Fig. 4. The scale of the ordinate is considerably different for the cropped and uncropped plots. Both Fig. 3 and 4 show that $^{15}N_2$ and N_2O

could not be detected beneath the lid after approximately 20 days. Denitrification for each of the six plots occurring as N_2O, N_2, and total is given in Table 1. In all cases, the amount of N_2 produced was much greater than N_2O.

Figure 5 gives soil solution NO_3^- concentrations derived from the fertilizer as a function of soil depth at approximately 125 days after application of the fertilizer to the h = -15 cm treatments. As expected, the smallest concentrations in the soil solution were in the manure plot because of a high amount of denitrification. Higher concentrations were measured in the cropped plot than in the manure plot. The greatest NO_3^- concentrations were measured in the uncropped plot. For the h = -70 cm treatments, the NO_3^- was just measureable at the 60- cm depth after approximately 115 days. Thus, most of the NO_3^- for this treatment was still in the upper 60 cm of the soil profile after 115 days.

DISCUSSION

Gas sampling within the soil profiles demonstrated that considerable $^{15}N_2$ was produced from denitrification of $^{15}NO_3^-$ fertilizer. Similar profiles were also measured for N_2O. For all plots except the manure plot at h = -15 cm, the $^{15}N_2$ concentrations were nearly constant with depth or decreased gradually near the surface. For the manure (h = -15 cm) treatment, however, the greatest concentration of $^{15}N_2$ and N_2O were measured at the shallowest sampling depth of 2 cm. Thus, considerable denitrification occurred very near the soil surface. The largest denitrification rates generally occurred within 6 to 24 hours after applying NO_3^-. For the relatively high soil temperatures at which these experiments were conducted, denitrification began very quickly with large initial rates. The generally rapid decrease in denitrification with time was due to decreasing NO_3^- concentrations in soil solution and the displacemnt of NO_3^- into less anoxic zones. Considerable O_2 could be measured from samples taken within zones where denitrification was occurring. Thus, there must have been sites or "pockets" within the soil which were anoxic due to high microbial activity and small O_2 diffusion. In general, the greatest anoxic development occurred in the upper 60 or 90 cm of this profile (Rolston et al., 1976).

The addition of manure to the soil greatly increased the rate and total denitrification. The addition of crop residues would also increase the denitrification potential. The presence of living plants greatly increased the amount of denitrification as shown by the differences in N_2 and N_2O flux at the soil surface of the cropped and uncropped plots. The consumption of O_2 through respiration of grass roots and addition of carbon to the system from sloughed roots increased denitrification by approximately three to four times over that of the uncropped plots at equal soil-water pressures. For the uncropped plot maintained at a soil-water pressure head of -15 cm, only 8 kg of N ha^{-1} were lost as N_2 and N_2O. Thus, it appears that very little denitrification of added NO_3^- will occur from uncropped Yolo loam even under the most adverse soil-water conditions. The maximum rate of denitrification in the cropped plot maintained at h = -15 cm was considerably less than that reported by Rolston et al. (1976). The field plot used by Rolston et al. (1976) had been cropped with perennial ryegrass for approximately two years before application of NO_3^-, and the soil may have been slightly wetter than that of this study since water was occasionally pulled into the soil atmosphere samplers. It appears that long-term cropping with grass may substantially increase the available carbon of the soil and the denitrification potential.

The soil-water pressure of the soil also has a large effect on denitrification. By decreasing the soil-water pressure head from -15 to -70 cm, denitrification in the manure plots was decreased from 280 kg N ha^{-1} to 47 kg N ha^{-1}. Decreasing the soil-water pressure head from -15 to -70 cm for the cropped plots decreasing the soil-water total denitrification from 34 to 9 kg N ha^{-1}. Decreasing soil-water pressure in the uncropped plots decreased denitrification from 8 to 4 kg N ha^{-1}. The very narrow range of soil-water pressure for which denitrification occurs for this particular soil, indicates that slight manipulation of soil-water content may be achieved to either increase or decrease denitrification depending upon particular objectives.

The large differences in denitrification among the cropped, manure, and uncropped plots of the h = -15 cm treatment also resulted in large differences in the concentration of fertilizer NO_3^- amount of denitrification resulted in the smallest NO_3^- concentrations in the soil solution. Denitrification in the uncropped plot of only 3% resulted in the largest

NO_3 concentration in the soil solution. The peak of the NO_3^- pulse for all three plots of the h = -15 cm treatment was at approximately 140 cm for 120 days after fertilizer application. On the other hand, for the h = -70 cm treatments, most of the NO_3^- was still in the upper 60 cm of the soil profile. An estimate of evapotranspiration was obtained from the water application rate for the h = -15 cm treatments, the volumetric water content of the soil profile, and the rate of movement of NO_3^- through the soil profile. Inasmuch as the profiles were kept constantly wet, it would be expected that evapotranspiration would be similar for all plots. Applying this estimated evapotranspiration to the h = -70 cm treatments gave a pore water velocity for the h = -70 cm treatments of approximately 0.5 cm day^{-1} as compared to 1.1 cm day^{-1} for the h = -15 cm treatments. From these estimates of pore water velocity, the peak of the NO_3^- pulse should have been at about 55 cm at 110 days for the h = -70 cm treatment. Soil solution samples taken at 110 days show a slight increase in NO_3^- concentration at the 60 cm depth of the h = -70 cm treatments.

The implication of denitrification on irrigation return flow water quality is that the concentration of NO_3 leaching below the crop root zone can be partially manipulated through denitrification of fertilizer. The carbon input and soil-water content may be manipulated to either increase or decrease denitrification as desired. The overall objective of nitrogen management, of course, is to maximize fertilizer use efficiency and minimize leaching of NO_3^- to ground waters. It is obvious from the results presented here that the addition of an organic carbon source to the soil such as manure greatly increased denitrification in the upper portion of the soil profile. Addition of manure and fertilizer to the soil would be undesirable in terms of fertilizer use efficiency unless the irrigation water could be managed to maintain soil-water pressures in the top part of the profile smaller than the value for which denitrification occurs (-70 to -100 cm for Yolo loam). A soil with

TABLE 1

Denitrification as N_2O, N_2, and total for the six treatments as determined from the accumulation of gas beneath a cover placed over the soil surface for a 1- or 2-hour period. The application rate was 300 kg N ha^{-1} as KNO_3.

	N_2O	*N_2*	*TOTAL*	
Treatment	*(kg N ha^{-1})*	*(kg N ha^{-1})*	*(kg N ha^{-1})*	*(% of fertilizer*
Manure, h = -15 cm	9.9	198	208	69
Manure, h = -70 cm	5.4	42	47	16
Cropped, h = -15 cm	4.3	30	34	11
Cropped, h = -70 cm	1.8	7	9	3
Uncropped, h = -15 cm	2.1	5.7	8	3
Uncropped, h = -70 cm	0.6	3.6	4	1

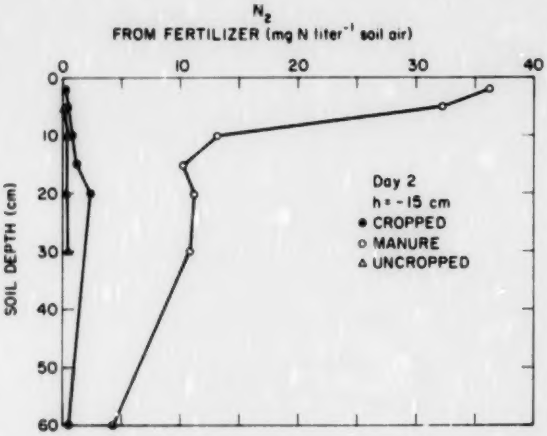

Figure 1. Representative concentration profiles of N_2 derived from the fertilizer within the soil of the cropped, manure, and uncropped plots at a constant soil-water pressure head of -15 cm.

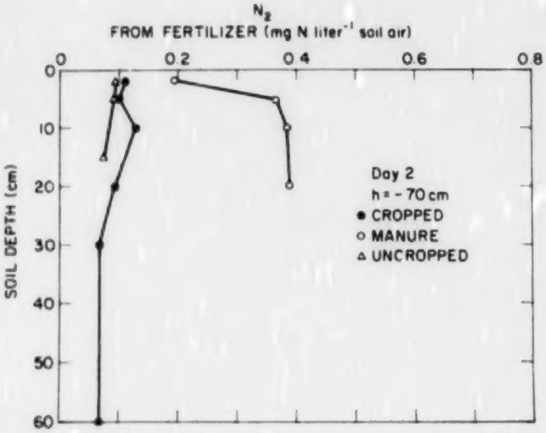

Figure 2. Representative concentration profiles of N_2 derived from the fertilizer within the soil of the cropped, manure, and uncropped plots at a constant soil-water pressure head of -70 cm.

low organic matter would result in the smallest denitrification and the largest NO_3^- leaching at times when a crop was not actively taking up part of the N applied.

The results of this research shows that denitrification occurs very rapidly after application of NO_3^- to a wet soil and that denitrification rates can potentially be very large. The growth rate of denitrifying organisms during wetting of initially dry soil, the amount of available carbon, soil physical and chemical properties, and length of irrigation will affect the amount of denitrification. The irrigation frequency and soil-water contents before, during, and after irrigation should have a large influence on the absolute amounts and rates of denitrification. The position of NO_3^- pulse in relation to the soluble or available carbon source of the profile will also greatly influence the amount of denitrification. The position of NO_3^- within the profile and the soil-water content may be manipulated through management of irrigation. Irrigation management practices to minimize NO_3^- in irrigation return flow waters may or may not be the same practices which would minimize denitrification to attain maximum fertilizer use efficiency. The proper management practices to attain minimal environmental change and maximal fertilizer N efficiency can be best determined from a thorough analysis of the fluxes of N in the soil including the volatile products of denitrification.

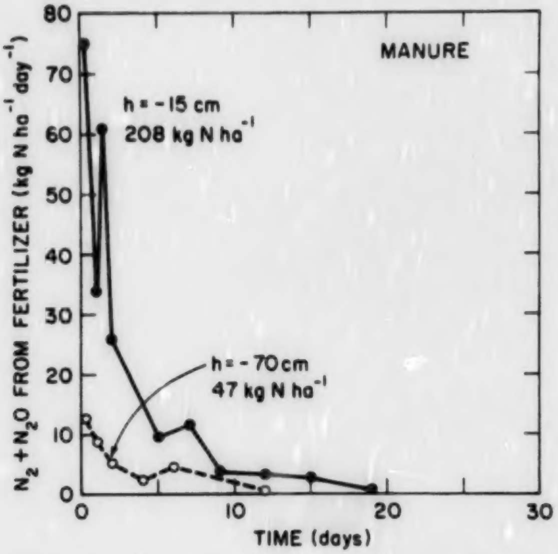

Figure 3. Total flux of gaseous denitrification products as a function of time after fertilizer was applied to the manure plots at two soil-water pressures (h). The number under each pressure head value is the total denitrification for that treatment.

ACKNOWLEDGMENTS

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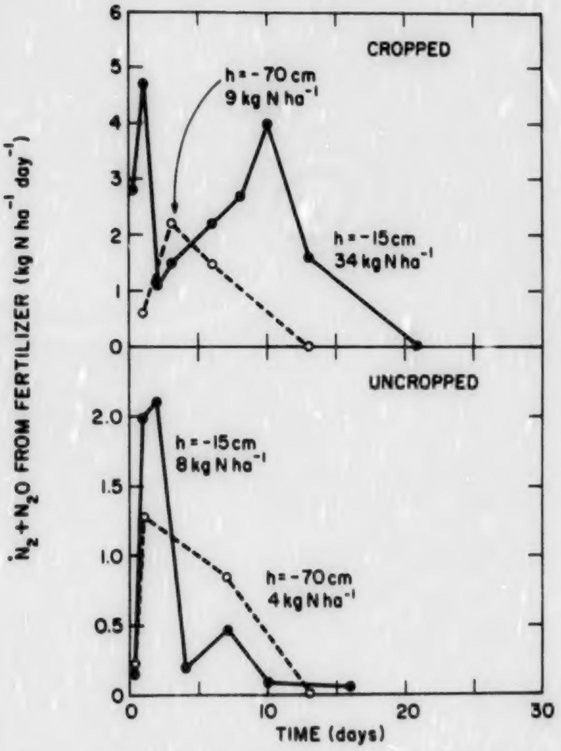

Figure 4. Total flux of gaseous denitrification products as a function of time after fertilizer was applied to cropped and uncropped plots at two soil-water pressures (h). The number under each pressure head value is the total denitrification for that treatment.

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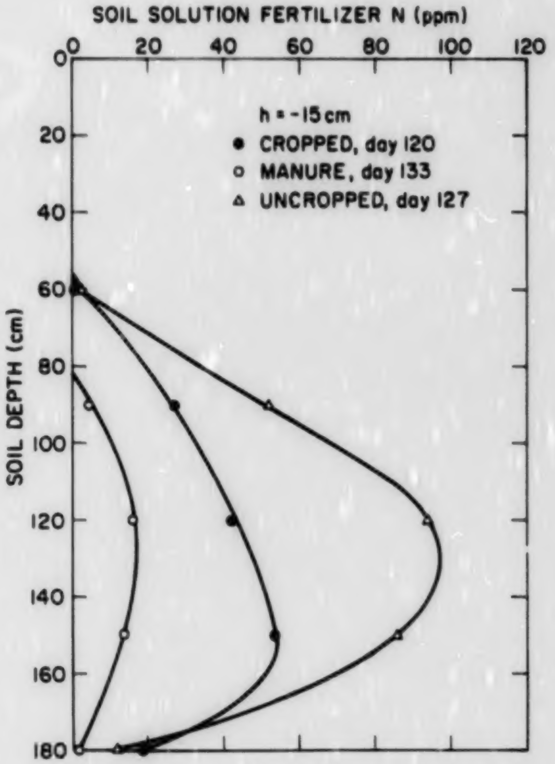

Figure 5. Concentration of fertilizer derived NO_3^- (ppm N) in the soil solution as a function of depth for the cropped, manure, and uncropped plots at a soil-water pressure head of -15 cm for approximately 125 days after fertilization application.

Soil Nitrate Concentrations in Corn Plots Treated with Isotopically Labeled Nitrogen Fertilizer

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ABSTRACT

Soil solution composition has been monitored for 3 years at depths ranging from 30 to 300 cm at an experimental site on Yolo fine sandy loam where ^{15}N-depleted ammonim sulfate has been applied at 0, 90, 180 and 360 kg N per year. Samples have been taken at approximately 2-week intervals during the growing season and less frequently during the winter and early spring. In unfertilized plots receiving 60 cm/yr irrigation water NO_3-N concentrations fluctuated widely near the surface, ranging from 3-4 up to about 35 ppm over a 2-1/2 year period. At lower depths fluctuations were not as great, but at 300 cm NO_3-N consistently remained above 10 ppm. At 90 and 180 kg-fertilizer N, the latter level being sufficient to produce the maximum grain yield, very little NO_3-N derived from fertilizer was found below 120 cm. However, at the 360 kg level, fertilizer-derived nitrate was found to constitute a significant fraction of the total at all depths down to 300 cm.

At another site on Hanford sandy loam where fertilizer rates of 0, 112, 224, 336, 448 and 560 kg N/year were used, soil solution nitrate concentrations were determined once a year by analysis of soil cores taken just after harvest. In this soil of low organic N content most of the residual nitrate in the soil was fertilizer derived. Below the 212 kg N level there was little residual nitrate, but it rose sharply as a function of N applied at levels above the 212 kg rate.

The data indicate that with good management, optimum corn production and minimum nitrate pollution are compatible goals, but it is impractical to maintain NO_3-N concentrations in the soil solution below the 10 ppm Public Health standard. Unfertilized plots which exhibited severe N deficiency had soil solution NO_3-N levels above 10 ppm much of the time.

INTRODUCTION

Since nitrate in groundwaters results from a dymanic, complex and highly interrelated series of nitrogen transformations and transport processes which are modified by biological, chemical and physical properties of soil, relating concentrations of nitrate in the subsoil to management practices is not a simple matter. Not least among the complicating factors is the gradual and continuous mineralization of soil organic nitrogen. The size of the organic pool is larger than is commonly realized. For example, if it is assumed that a soil has only 0.05% organic N in the surface meter, mineralization of 2% per annum would contribute 150 kg N per hectare in the form of nitrate to the soil system. Much larger amounts would be produced in soils of higher organic content, particularly in cases where the soils are deep and freely drained.

A number of recent articles have dealt with the relationships of fertilizer and other practices to accumulations of nitrate in soils, plants and waters, including some excellent reviews (1, 2, 3, 4, 5, 6). For the most part, previous work in this area has had no means of discrimination between nitrates derived from fertilizer and that from other sources, including mineralization of organic N within the soil. The possibility of

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establishing quantitative relationships between nitrate concentrations in effluents from irrigated lands and nitrogen fertilizer management has been made more feasible by the availability of fertilizer materials which are labeled with stable isotopes. In particular, the production of ^{15}N-depleted materials in quantities sufficient for full-scale field trials at costs which are not unreasonable for field operations has represented a major breakthrough.

The normal composition of nitrogenous materials as they occur in nature is about 0.366 atom % ^{15}N and 99.634 atom % ^{14}N. Any nitrogen-containing substance which differs significantly from this isotopic composition can be used as a tracer. Compounds containing less than 0.005 % ^{15}N are now available in ton quantities. If the minimum acceptable difference from the natural isotopic composition is taken as 0.01 atom % in order to ensure two significant figures in calculation, it can be determined that essentially pure ^{14}N materials can be diluted about 30-fold without losing their isotopic identity. This acceptable range of dilution is satisfactory for evaluating the contributions of labeled fertilizer to nitrates in soil solutions, even when taken at considerable depth.

This paper describes two field trials utilizing ^{15}N-depleted fertilizer in which measurements of soil nitrates were made and in which determination of the isotopic composition of the nitrate samples permitted the computation of the proportion which was derived from the applied fertilizer.

EXPERIMENTAL PROCEDURE

In 1973 field experiments were established at two locations, one at the University of California in Davis and the other at the Kearney Horticultural Field Station near Reedley in the San Joaquin Valley. At the Davis site a 2.2 hectare tract of Yolo fine sandy loam was laid out in four blocks with four fertilizer rates and three irrigation levels. Fertilizer rates were 0, 90, 180 and 360 kg N as ^{15}N-depleted ammonium sulfate, all applied at planting time to an area 4.57 x 6.1 m within each plot. The irrigation treatments were 20, 60 and 100 cm of water applied over the growing season at 2-week intervals in amounts intended to follow the consumptive use curve. These amounts are equivalent to 1/3, 3/3 and 5/3 of the evapotranspiration requirement for corn at this location, based on weighing lysimeter data obtained in previous years at this site. All plots received a pre-plant irrigation to bring the plots to field capacity. The field was instrumented with porous ceramic suction probes for extracting soil solution at depths of 30, 60, 120, 180, 240 and 300 cm. Two probes were located at each depth in 24 of the 48 plots, and in the other 24 plots duplicate probes were placed at 240 and 300 cm depths. Only the data from the 300 cm probes are presented in this paper, and the values given generally represent the mean of 8 replicate probe samples, although there are some exceptions since every probe did not yield a sample at every sampling date. Samples were collected at approximately biweekly intervals during the growing season and less frequently during the intervening months, when sampling frequency was determined by rainfall pattern. The soil solution samples were analyzed for nitrate and ammonium and the isotopic composition of the inorganic N determined with a mass spectrometer. For all practical purposes the inorganic N was identical with nitrate-N, since very little ammonium was found.

Tensiometers were located in the plots at the same depths as the soil solution probes, and in addition, wells for neutron moisture meters were located in each moisture treatment area. Frequent readings were made throughout the year.

The plots were planted to corn, with all above-ground portions of the crop removed at harvest time. Plant uptake of labeled N was determined by analysis of grain and stover. After harvest, soil cores were taken to a depth of 300 cm, two cores in each plot. Increments of 30 cm were analyzed for inorganic N by extraction with N KCl, and the combined $NH_4^+ + NO_3^-$ in the extract analyzed in the mass spectrometer. Concentrations on a soil solution basis were calculated by using the neutron meter readings to determine soil moisture at the time of soil sampling. These values as reported reflect not only nitrate in the soil solution, but also absorbed ammonium which is potentially convertible to nitrate.

At the Kearney site 24 plots, each 0.27 hectare in area, were established on Hanford sandy loam. Annual fertilizer rates employed were 112, 224, 336, 448 and 560 kg N/ha, of which one third was applied pre-plant and the other two-thirds later as a side-dressing. Irrigation was uniform for the entire area, which received 67 cm of water during the growing season, This amount was 10% in excess of the calculated evapotranspiration. At this location no probes for sampling soil solution were installed. Soil samples were obtained after crop harvest to a depth of 180 cm in 1973, to 240 cm in 1974 and to 420 cm in 1975. Three cores were taken from each plot, with samples at 30 cm increments, and composited by depth for analysis. Nitrate was extracted from the soil samples with water and determined by Devarda reduction and steam distillation. Moisture contents were determined by oven-drying field samples.

As at the Davis site, corn was planted at the Kearney location, but in the latter case only the grain was removed, with all other plant parts returned to the soil after harvest.

RESULTS AND DISCUSSION

The rainfall pattern over the three cropping seasons at the Davis location is recorded in Table 1. These amounts may be put in perspective by noting that the total stored water in the top 3 meters of soil ranged from about 70 to 120 cm from the driest to the wettest conditions, respectively.

TABLE 1

Monthly rainfall at the Davis site from July 1, 1973 to January 1, 1976.

	Monthly total, cm		
Month	*1973*	*1974*	*1975*
January		8.91	0.61
February		1.47	17.91
March		13.00	11.38
April		2.31	1.37
May		0	0
June		0.74	0
July	0	1.65	0.28
August	0	0	0.13
September	.43	0	0
October	3.99	3.05	6.17
November	14.73	2.26	0.68
December	10.69	9.47	0.97

Suction Probe Data

Before discussing the results it is appropriate to comment on the reliability of data obtained by sampling soil solution with suction probes. The variability among replicates were considerable, as is shown in Table 2,which presents means and standard deviations for samples obtained on two dates in 1975. The dates were selected at random, simply to show typical data. Even with 8 replicates the standard deviations ranged from 36 to 78% of the mean for total soluble N, and were even higher for tagged N. These observations emphasize the difficulties attendant to monitoring soil solution composition in a field situation, even with a large number of probes.

TABLE 2

Means and standard deviations of N concentrations in soil solution samples collected at the 300 cm depth in plots receiving 100 cm irrigation water.

N level, kg/ha	*Soluble N, ppm*	*Std. Dev. ppm*	*Tagged N, ppm*	*Std. Dev. ppm*
		July 15, 1975		
0	7.1	2.8	—	—
90	9.4	4.4	0.58	0.34
180	13.3	5.9	1.17	0.65
360	31.4	13.6	13.8	8.9
		August 12, 1975		
0	8.4	3.4	—	—
90	10.5	3.8	0.81	0.88
180	14.3	6.3	1.80	2.96
360	39.7	31.0	19.0	14.1

Concentrations of inorganic N at the 300 cm depth are presented in a series of graphs showing temporal trends from July 1, 1973 to January 1, 1976.Where fertilizer was applied, concentrations of inorganic N derived from fertilizer are also shown. Since fertilizer was applied in April or May of each year, the values shown represent cumulative effects, there being no way to distinguish between applications in successive years. The values at 300 cm are unaffected by plant uptake, since few if any roots penetrate to that depth, and are probably representative of solution which eventually reaches the water table. It may be noted as an aid to interpretation of the curves presented that the soil was sufficiently well supplied with available nitrogen that no yield response to any level of fertilizer addition was obtained in 1973. However, in 1974, 90 kg of fertilizer N was required to produce maximum yield, and in 1975 a yield response was obtained up to 180 kg additional N. In all three years the yield was significantly lower in plots receiving only one-third of the evapotranspiration requirement (1/3 ET). Reference to Figure 1 shows a general downward trend in concentrations of inorganic N in the unfertilized plots receiving 20 cm irrigation after 1973, but values did not fall as low as 10 ppm at any time. Where 90 kg N was applied concentrations went nearly up to 50 ppm in the latter part of 1974, but decreased rather sharply thereafter, reaching a low of about 16 ppm at the end of 1975. The amount of fertilizer derived N reaching the 300 cm depth was almost negligible. In Figure 2 it will be noted that at 180 and 360 kg fertilizer levels very sharp increases in soluble N were observed during the summer of 1974, with values in excess of 50 ppm N being attained. At the 180 kg fertilizer rate concentrations declined progressively through 1975, but at the 360 kg rate concentrations remained high. In the latter instance, a significant proportion of the total soluble N was derived from the added fertilizer. In these plots receiving inadequate water for maximum crop production high concentrations of soluble N are perhaps not surprising, but the minimal contribution of fertilizer to these levels at the 90 and 180 kg rates is noteworthy.

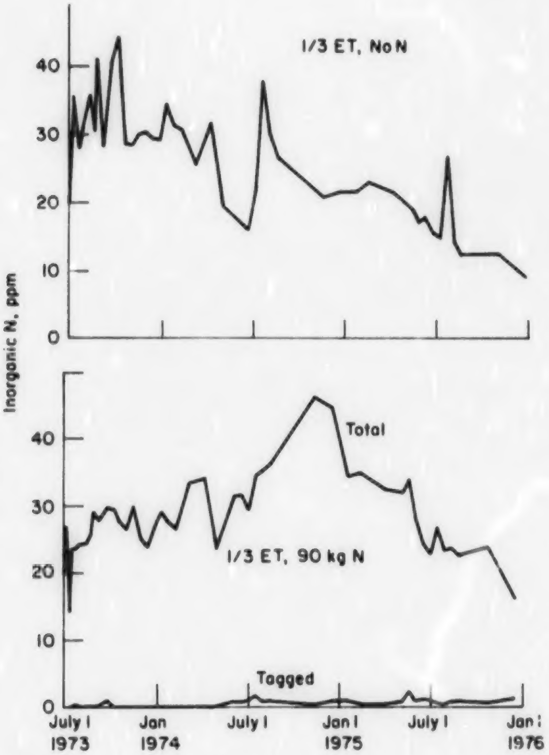

Figure 1.

Similar data for the 1 ET irrigation treatment are presented in Figures 3 and 4. With more water applied to the soil, the concentrations attained were not quite so high as at 1/3 ET, but the same general observations are applicable. Again, only at the 360 kg N rate did a significant amount of fertilizer N reach the 300 cm depth. Data for the 5/3 ET irrigation treatment are presented in Figures 5 and 6. In these curves the influence of the heavy rains which fell in March, 1974, are more evident in a temporary reduction in soluble N concentrations. With reference to Figure 6, it will be noted that concentrations of tagged N in plots receiving 360 kg N increased progressively during 1974 and 1975. Figures 3 and 5 show that in unfertilized plots where water was adequate soluble N did not approach values as low as 10 ppm until the latter part of 1975, in spite of the fact that yields were severely depressed by defficiency of nitrogen. For example, in the 1 ET treatment area grain yields in the check plots were 59% of the optimum obtained in 1974 and only 44% in 1975.

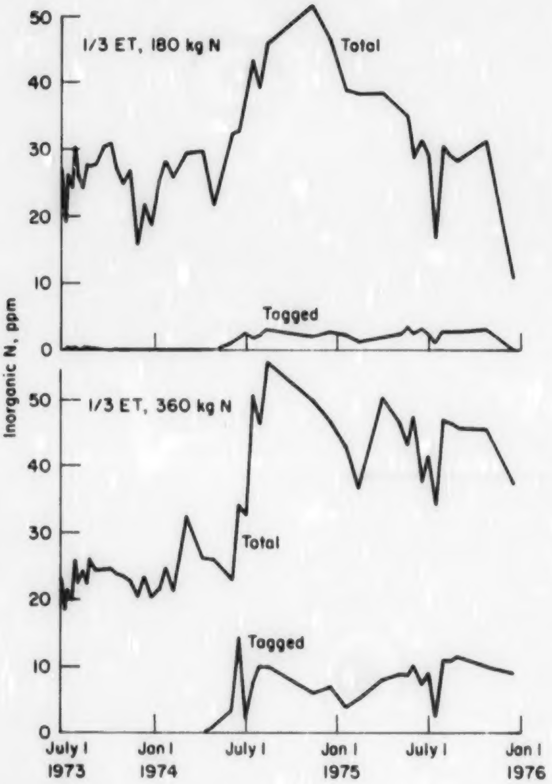

Figure 2.

Data from Soil Cores

Concentrations of inorganic N obtained from soil cores at the Davis site in October, 1975, are presented in Figure 7. These are expressed on a soil solution basis for the layer of soil between 180 and 300 cm depths. As expected, concentrations were higher in the plots receiving least water. Mean values for this 120 cm thick layer were consistent with probe sample values in showing concentrations above 10 ppm N in the unfertilized plots. Concentrations did not increase sharply with increasing fertilizer application rates up to the point of maximum yield, 180 kg N/ha, but increased significantly with the further addition of N at the 360 kg level.

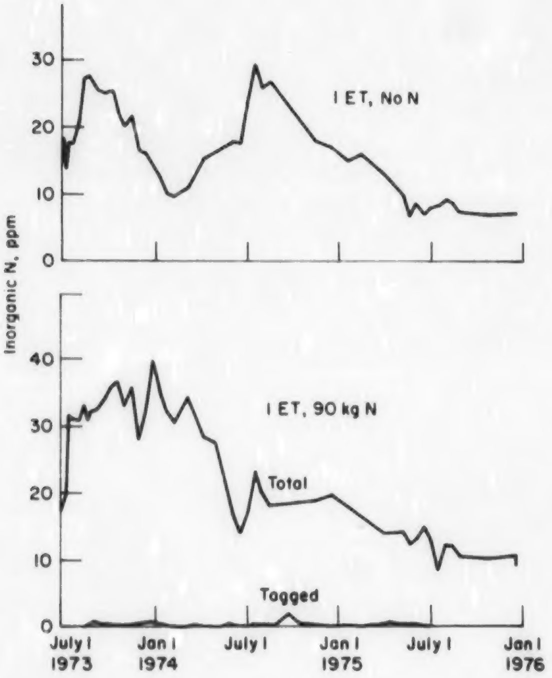

Figure 3.

The same general conclusions are applicable at the Kearney site, data for which are presented in Figure 8. Here the fertilizer-derived nitrate is also identified. In this extremely nitrogen-deficient soil nitrate-N was about 9 ppm on the soil solution basis in the 180-300 cm soil layer after crop harvest in 1975. In these plots grain production in the unfertilized plots was only 18% of that in plots receiving 224 kg N. There was no appreciable contribution of fertilizer N to nitrate in the 180-300 cm layer at fertilizer rates of 224 kg and below, but the concentration increased sharply above this fertilizer rate, with concentrations in excess of 100 ppm being attained at the 560 kg N rate.

It might be argued that the lack of fertilizer N in the soil solution at fertilizer rates below the optimum is due to preferential utilization of fertilizer N by the crop, thereby leaving more of the soil N available for leaching. While it is true that biological exchange involving microbial activity undoubtedly occurred to some degree, resulting in some fertilizer N being immobilized and some soil N mineralized, the plant uptake data presented in Tables 3 and 4 show that utilization of soil N was actually enhanced by fertilizer additions up to the levels of optimum yield, and even beyond in several instances. The optimum yield at the Davis site in 1973 was obtained with no fertilizer, with 90 kg N in 1974 and with 180 kg N in 1975, whereas the optimum rate at the Kearney site was 212 kg in all three years.

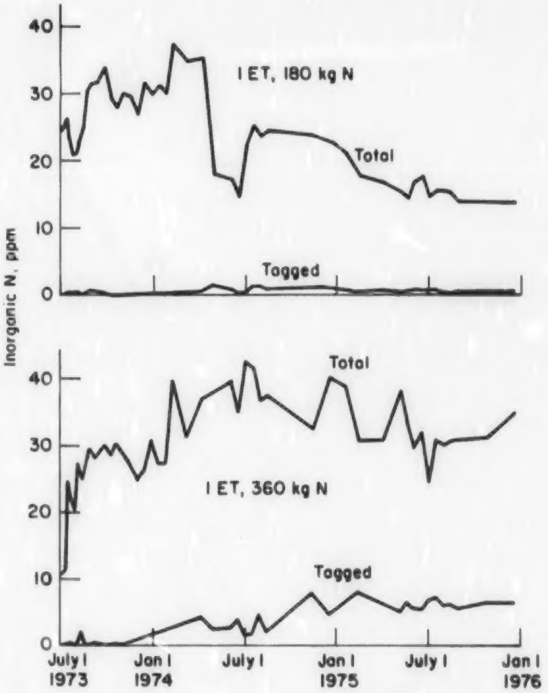

Figure 4.

The data indicate that with careful management of irrigation water and fertilizer rates, maximum corn production on these soils is compatible with minimum nitrate pollution hazard. However, it is not realistic to attempt to maintain nitrate-N concentrations in the soil solution below 10 ppm. In any event, total mass flow of nitrate below the root zone is obviously a much more important consideration than concentration *per se*.

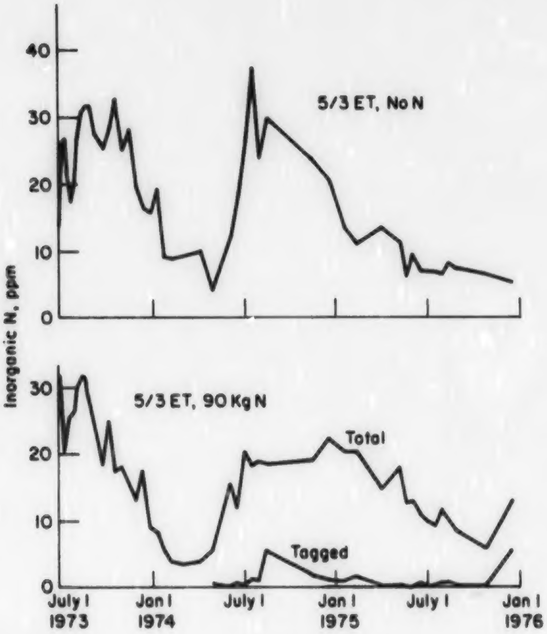

Figure 5.

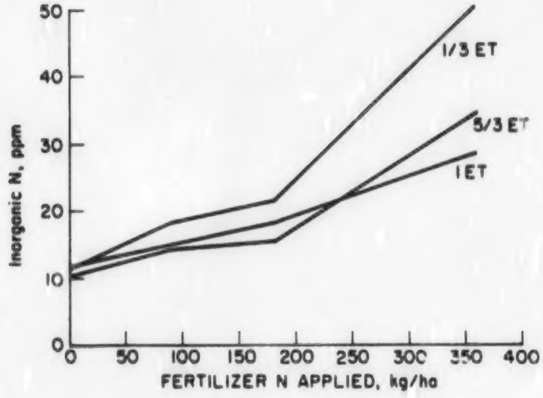

Figure 7.

TABLE 3

Uptake of soil N by crops as affected by fertilizer rate, Davis site.

Fert. rate kg/ha	*1/3 ET*			*1 ET*			*5/3 ET*		
	1973	*1974*	*1975*	*1973*	*1974*	*1975*	*1973*	*1974*	*1975*
					kg/ha				
0	155	83	64	155	120	90	145	105	77
90	139	99	102	148	134	108	136	133	100
180	110	93	105	108	115	124	103	117	101
360	95	97	107	84	87	82	75	82	83

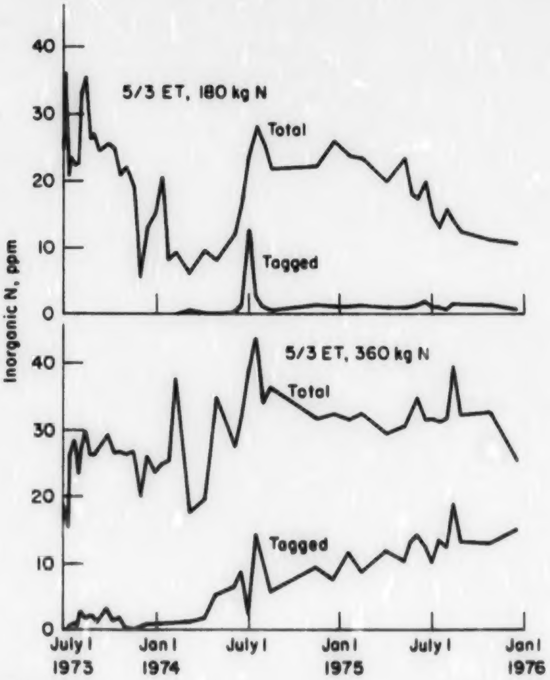

Figure 6.

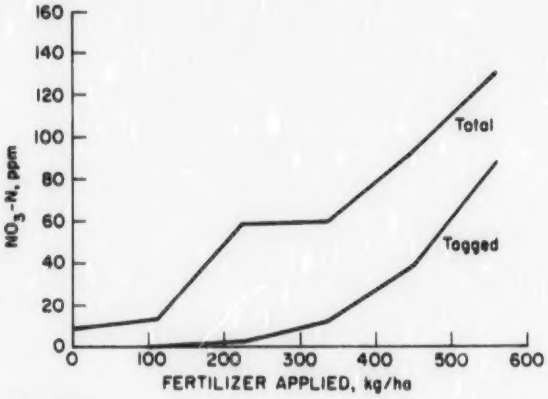

Figure 8.

TABLE 4

Uptake of soil N by crops as affected by fertilizer rate, Kearney site.

Fertilizer rate kg/ha	*1973*	*1974*	*1975*
		kg/ha	
0	34	35	40
112	63	36	59
224	80	37	69
336	66	25	60
448	57	23	43
560	53	18	44

ACKNOWLEDGMENT

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Theoretical and Experimental Observations of Water and Nitrate Movement Below a Crop Root Zone

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ABSTRACT

A report of the progress of an experiment which attempts to deal with the spatial variability of a field soil is presented. The experimental objective is to measure the flux of water and nitrate leaching below the root zone of a crop by examining the behavior of nitrogen applied to a corn crop grown under irrigation.

A primary objective of this conference and that of the Environmental Protection Agency is to be able to interpret periodic measurements of water and its dissolved constituents at specific locations at and below the soil surface in relation to irrigation return flow quality management. The objective is relatively new to all of us, regardless of our scientific or engineering discipline, owing to the fact that we and most other agriculturists throughout the world have used the yield of a crop or a sequence of crops as the foremost measure of good irrigation management practices. Those measurements have occasionally been complemented by gross estimates of water and salinity budgets, partially substantiated by infrequent monitoring of the quality of drainage effluents in areas of poor drainage or salinity hazard. By in large, measurements of soil and water have generally been restricted to those within the crop root zone to ascertain capacities of available water and plant nutrients and estimates of total salinity or leaching fractions. Today, owing to a greater concern regarding the quality and quantity of our water resources brought about through both private and governmental sectors, researchers have quickened their pace to be able to understand what happens below the soil surface, and below the root zone. We are a long way from a fully developed technology to measure and interpret events below the soil surface to manage irrigation return flow quality. We are also a long way from a fully developed technology to mathematically model and interpret measurements made below the soil surface to manage irrigation return flow quality. This conference is a testimony to the latter two statements with research presentations often falling into one of two classes — (1) Intensive measurements and/or calculations restricted to a single location without regard to their interpretation and simulation over larger land areas, and (2) Extensive measurements and/or simulations for large land areas without adequate regard to their verification at specific locations. The former are oftentimes not suited to relatively small rates of change evaluated over long time intervals — years or decades, while the latter are oftentimes impractical for short-time events. Both are potentially affected severely by the spatially varying properties of the soil. That is to say, the spatial variability of soils poses a problem to the researcher in identifying a mean value of a soil parameter even for a relatively small experimental site, and because of this problem, the researcher hesitates to extrapolate results to larger land areas or give such values to mathematical modelers with relatively little appreciation of their experimental uncertainty. On the other hand, soil-water-solute measurements taken at a few specific times and locations may lead rightfully or wrongfully, owing to spatial variability of soils, to an acceptance of a particular mathematical model.

The purpose of this paper is to report the progress of an experiment currently being conducted in an attempt to deal with the spatial variability of a field soil with the objective to

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measure the flux of water and nitrate leaching below the root zone of a crop. The experiment, which is a part of a larger project partially supported by NSF, examines the behavior of nitrogen applied as ^{14}N in ^{15}N-depleted fertilizer to a crop of corn being grown under irrigation. The experiment has thus far covered four growing seasons. The experimental site is located in Davis, California, on a recent alluvial fan derived from mixed but dominantly sedimentary rock sources and is classified Yolo loam and Yolo silt loam.

There are three irrigation regimes replicated four times. Hence, there are 12 large plots which are managed as individually irrigated units, and within each of these plots, fertilizer is applied to four subplots as ^{14}N in ^{15}N-depleted NH_4SO_4 at O, 90, 180 and 360 kg per ha. The water treatments correspond to 1/3, 3/3 and 5/3 of the normal evapotranspiration (ET) requirements of the corn crop as determined by several years of experience with corn in the same field. These correspond to about 20, 60, and 100 cm of irrigation water applied, respectively. Selection of these treatments was based on the objective of providing for three different soil moisture regimes with corresponding differences in the flux of water that would drain from the root zone. Consequently, the 5/3 ET water treatment would provide excessive water that will drain out of the root zone during and after the growing season and leach mobile nitrogen. The 1/3 ET water treatment does not provide equivalent water lost by ET and drainage will be minimized. Since the Yolo soil is deep and stores a significant quantity of water provided by winter rainfall and pre-irrigations, the corn corp will not suffer severe stress during the growing season. Drainage from the 3/3 ET water treatment is expected to be intermediate and might represent normal irrigation practices. Irrigations are applied at 14 day intervals providing a quantity of water to each water treatment commensurate with the estimated requirements based on evapotranspiration rates. It should be understood that the experiment does not require applications corresponding exactly to the water loss as calculated by ET since the treatments hav been established only as guidelines to achieve three different moisture regimes.

Soil water pressure measurements are made using tensiometers placed 30, 60, 120, 180, 240 and 300 cm below the soil surface. Two plots in each replication of each water treatment have two tensiometers at each depth and two other plots in the same replication have two tensiometers each at 240 and 300 cm. Thus, there are 48 tensiometers at each depth except at 240 and 300 cm where there are 96 at each depth for a total of 432. Figure 1 is a diagram of the configuration in each water treatment plot. Measurements of soil water pressure are taken usually immediately before and after an irrigation and in the interval between irrigations. There are an equal number of suction probes in the same configuration for extracting the soil solution. All instruments are buried at or below the 30 cm depth so that none protrude above the soil surface to interfere with cultural practices. This required a modification in design since all tubing also is buried within the plot area and comes to the surface in the roadways between plots. Two neutron access tubes are located in each replication of the water treatments as shown in Figure 1, for a total of 24 locations. Neutron readings are made at 15 cm intervals to a depth of 300 cm twice a week during the growing season and through the fallow season on a reduced schedule.

Hence, during the past four years we have obtained thousands of simultaneous measurements of soil water content and soil water pressure head at the above-mentioned depths at two locations within each irrigated plot. Before the data can be used in any constructive way, it is necessary to examine them in view of the uncertainty of each value, as well as to recognize how to deal with their distribution to obtain a mean value and/or other useful measure of their distribution. The uncertainty stems from instrument and observer error while

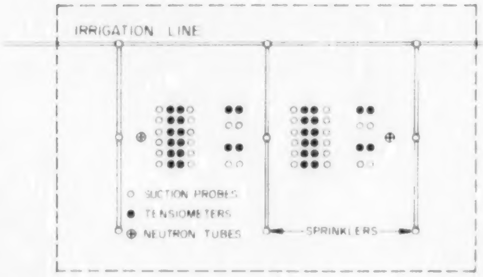

Figure 1. Schematic diagram of an irrigated plot showing the relative locations of suction probes, tensiometers, neutron meter access tubes, and sprinkler heads.

the distribution of observed values stems, in addition to that uncertainty, to differences in soil water regime caused by (1) the rainfall and irrigation patterns, (2) patterns of water extraction owing to the corn roots being nonuniformly distributed within the soil profile both with respect to space and time, and (3) the spatially varying properties of the soil as well as their time-dependent nature owing to hysteresis. For the purposes of this discussion, we shall concentrate on points 2 and 3, without neglecting point 1, or the error of the measurements.

Let us first examine measurements of the soil water characteristic (soil water content versus soil water pressure) taken in four arbitrarily selected locations that were not cropped but covered with plastic sheets within the experimental site. These measurements taken in the absence of corn plants are shown in Figures 2 and 3 for soil depths 60 cm and 120 cm, respectively, for only a 30-day period following the application of a large quantity of water. Data for soil water content are mean values of four measurements and those for soil water pressure head are mean values of three measurements. Notice that the curves in Figure 2 for plots 1 and 3 are nearly identical while that for plot 2 and that for plot 4 show progressively less water retained at soil water pressure heads of -200 cm. Similarly, in Figure 3, for the 120-cm depth, the curve for plot 1 is completely different from those for plots 2, 3 and 4. The solid line in each graph is

$$h(\theta) = a\langle \exp[\rho(\theta - \theta_s) - 1]\rangle \qquad [1]$$

where ρ equals $b\theta_s^{-1}$, b is a parameter common to all locations, θ_s denotes the saturated water content, and a is a parameter the value of which depends upon each location. These differences in soil water characteristic curves shown in Figures 2 and 3 also exist at the other soil depths. Even greater differences exist within and between plots illustrated in Figure 1. The net result is that the natural spatial variability of a soil precludes an assumption that soil water regimes in plots treated identically will behave similarly. It demands that a special effort be made to account for point measurements being biased away from the norm owing to localized soil properties in order to integrate these mea-

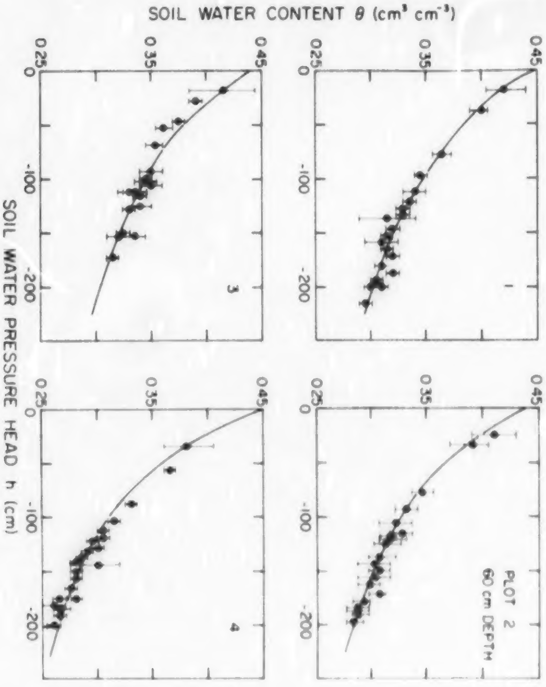

Figure 2. Soil water characteristic curves measured at the 60-cm depth in four locations within the experimental site. The solid lines are given by equation (1).

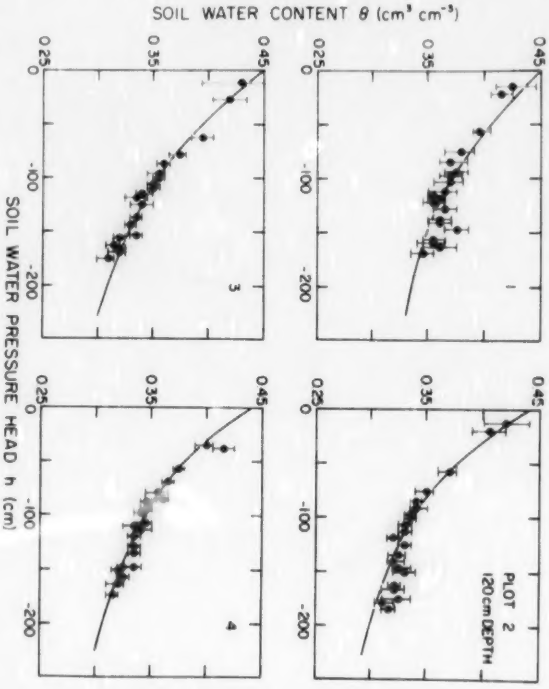

Figure 3. Soil water characteristic curves measured at the 120-cm depth in four locations within the experimental site. The solid lines are given by equation (1).

surements in such a manner as to represent the mean over the total area under consideration — an experimental plot, four plots all treated the same, or an entire field.

We demonstrate in Figure 4 a scaling technique similar to that suggested by Warrick, Mullen and Nielsen (1977) to coalesce the data of Figures 2 and 3 into a single curve. Full details will be available in a publication of Simmons, Biggar and Nielsen (1977). All data points for each of the graphs of Figures 2 and 3 are given in Figure 4 with the solid line described by

$$h(S) = a_m \langle \exp[b(S - 1) - 1] \rangle \qquad [2]$$

where S equals θ/θ_s, a_m is the scale mean coefficient which holds for all locations, and b is that parameter given in Equation [1]. The value of a given in equation (1) for a specific location is that of a_m divided by the scale factor α explained in Simmons *et al.* (1977). Figure 4 illustrates that the data from Figures 2 and 3 can be coalesced into a single curve satisfying equation (2) that can be used in mathematical analyses for a specific location within a plot (for a particular value of α) or for a much larger area if the mean value of α is known. In a similar fashion, the hydraulic conductivity K can be coalesced by the equation

$$K = \alpha^2 K_m \exp[c(S - 1)] \qquad [3]$$

where K_m is the scale mean water-saturated hydraulic conductivity which holds for all locations and K_o (equal to $\alpha^2 K_m$) is the water-saturated hydraulic conductivity which is dependent upon location, and c is a parameter common to all locations. Hence, it appears that the soil water properties [θ(or S) versus h and K versus θ(or S)] may be scaled to provide the basis of calculations of soil water transport and retention for any area desired provided that appropriate values of the scale factor are available. Figure 5 shows measured values as well as calculations of the soil water flux at the 120-cm depth in plots 1 and 2 with the value 35.3 for the parameter in the equation being derived from the average value of α for the four plots.

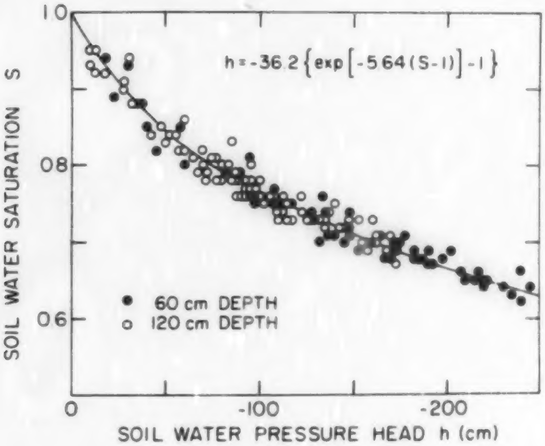

Figure 4. Scaled soil water characteristic curve for the data given in Figures 2 and 3. Solid circles and open circles represent the 60 and 120 cm depths, respectively.

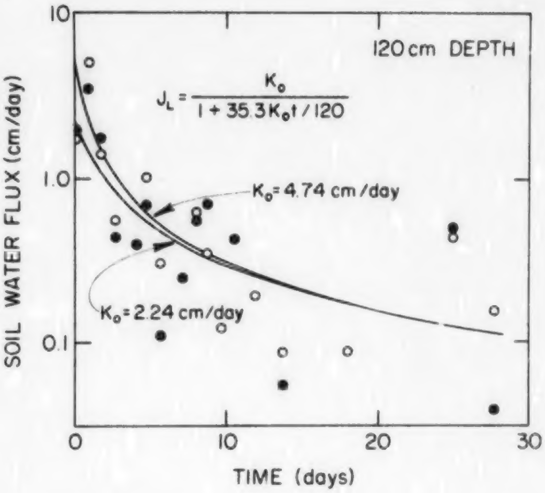

Figure 5. Calculated and measured values of soil water flux at the 120 cm depth of plots 1 and 2.

Using the thousands of paired values for θ and h stemming from measurements with neutron meters and tensiometers taken in the 12 plots during the past four years, we have ascertained 72 values of α (6 soil depths times 12 plots) which represent the experimental site. These values, shown in Figure 6 as a cumulative probability graph, are not normally distributed, but skewed with a few values exceeding 5 lying to the right off of the graph. The α values are better described as a log-normal distribution having a mean of 0.91 and a mode of 0.38.

The impact of the spatial variability of the soil water properties reflected through the values and distribution of α is illustrated in Figures 7 and 8 where the soil water flux at the 240 cm depth and the average water content from the soil surface to that same depth are given as a function of drainage time in the absence of corn roots for values of α equal to 0.4 and 2.0. During early stages of drainage, values of the soil water flux differ by ten-fold and after 20 days of drainage, the soil location characterized by an α equal to 0.4 contains 20 cm more water in the profile to the 240-cm depth than the soil location characterized by an α equal to 2.0. These values are typical of those manifested within an experimental plot. It is readily apparent that a few measures or estimates of K, θ, and/or h within field plots may easily lead to unreliable conclusions, and that a thorough analysis of the inherent homogeneity (or heterogeneity) of the site is required before meaningful mass balances or rates of water and nitrate transport may be simulated (or verified) by mathematical models.

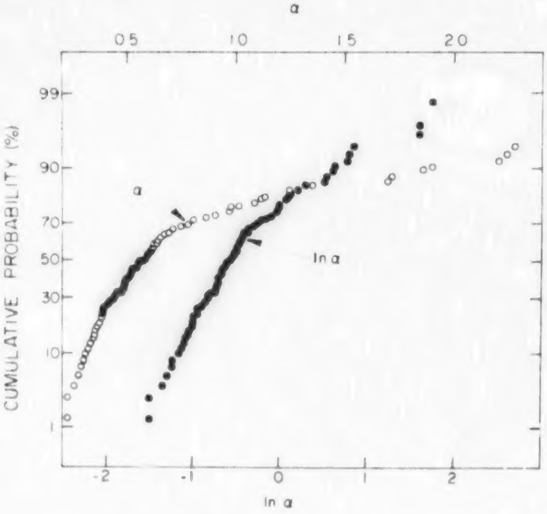

Figure 6. Cumulative probability graph of 72 values of α (and ln α) measured at six soil depths in each of the twelve irrigated plots cropped to corn.

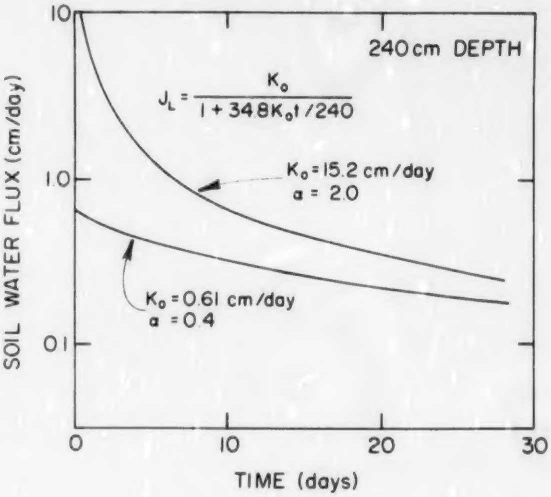

Figure 7. Soil Water flux at the 240 cm depth versus drainage time after a heavy irrigation in the absence of plants calculated using two sets of values of K_o and α.

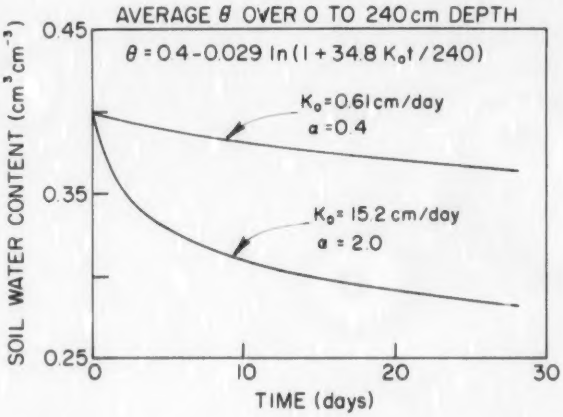

Figure 8. Average soil water content from the soil surface to the 240-cm depth corresponding to the conditions given in Figure 7.

In the presence of a crop, the movement of water and solutes in a soil profile reflect soil properties dealt with above, as well as space and time dependent nature of the crop properties. We include both of these properties in a simulation model (Gupta *et al.*, 1977) to illustrate the importance of recognizing and quantifying the spatial variability of soils on the magnitude of the soil water flux within and below the root zone of the corn crop in our experiment. It is not our intent here to justify the salient features of the computer program used to simulate the soil water movement, but we do wish to make clear the concepts included in the calculations. Features above the soil surface included (a) the soil water flux during sprinkler irrigation was 0.5 cm per hour, (b) lysimetric evapotranspiration measurements for corn in the same experimental area were appropriately proportioned into soil surface evaporation and potential transpiration based upon leaf area indices, and (c) actual transpiration was linked to potential transpiration as a function of the soil water content. Features below the soil surface included (a) root growth as a function of days as measured previously for corn on the same site, (b) water absorption by roots based on the application of Darcy's equation and root density as a function of soil depth and time, and (c) a water table sufficiently deep to assume a unit hydraulic gradient far below the root zone.

Figure 9 shows simulations of the soil water flux at three soil depths from planting time (t = 0 when the soil water content was assumed to be 0.32 cm^3 cm^{-3}) to near harvest (t = 131 days) for the 5/3 ET (100 cm) irrigation treatment during the summer of 1975. Calculations are based on measured values of hydraulic conductivity and the soil water characteristic for two scale factors 0.634 and 2.36. The former is larger than the mode but smaller than the mean of the distribution given in Figure 6, while the latter reflects about 10% of the observations expected in the field.

The seven peaks (in each graph) manifested in Figure 9 reflect the seven irrigations of different amounts of water applied per irrigation (3, 11, 18, 19, 18, 18 and 15 cm, respectively) made during the growing season. For the large value of α (corresponding to large values of K), the water flux reaches values of about 4 and 1 cm per day at the 105 cm and 210 cm soil depth, respectively, soon after an irrigation. For the small value of α, the corresponding water fluxes are only 1 and 0.2 cm per day. As the growing season progresses, notice that for the smaller value of α, the soil water flux gradually increases at all soil depths, reflecting a small increase in the amount of water retained within the soil profile. Table 1 shows the cumulative amount of water passing several soil depths up to day 123. Major differences exist throughout the soil profile for the two values of α which would contribute to different levels of leaching nitrate or other solutes within the soil.

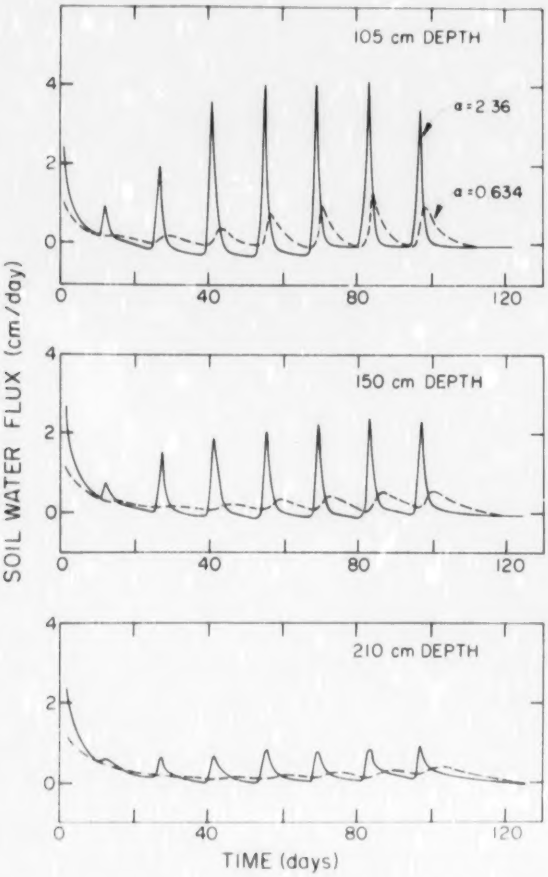

Figure 9. Soil water flux at three soil depths calculated for two values of α and the conditions for the 5/3 ET (100 cm) irrigation treatment planted to corn at t = 0.

We wish to emphasize that the fluxes shown in Figure 9 are not atypical — in fact, they could be observed simultaneously within the same plot. On the other hand, depending upon the average soil water content, observations of the soil water flux within a field plot could be further or closer together than those illustrated in Figure 9 — closer for dry soil, and further for wet soil. In general, the wetter the soil, the greater will be the variability of observations of soil water flux, and vise versa, for a given irrigation or water application.

We have not yet coupled the soil water flux with concentrations of the soil solution to obtain the flux of nitrate within and below the root zone. As mentioned in the introduction, this is a progress report, and we have not finished analyzing the spatial and temporal variation of nitrate concentrations measured in the soil solution extracted through the suction probes. A cursory examination of their values indicates that they are highly variable and that they manifest a behavior similar to those observed by Biggar and Nielsen (1976) in the absence of a

TABLE 1

Cumulative amounts of water (cm) passing through several soil depths up to day 123 of the growing season for corn irrigated at a rate of 5/3 ET.

Scaling Factor	*Soil Depth (cm)*						
(α)	*7.5*	*22.5*	*45*	*75*	*105*	*150*	*210*
0.634	71.0	54.7	43.2	31.4	25.2	23.1	24.7
2.36	71.0	57.1	51.8	40.4	32.6	27.6	26.0

growing crop. We shall have to incorporate into the analysis made by Biggar and Nielsen the various transformations of the nitrogeneous species as well as their uptake by the corn crop.

ACKNOWLEDGMENT

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Water Management

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Minimizing Salt in Return Flow by Improving Irrigation Efficiency

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ABSTRACT

Return flow from irrigated agriculture has been identified as the major source of salinity in the Colorado River that may be controlled. Thus, if the trend of increasing salinity is to be reversed, it appears that irrigated agriculture must bear a large portion of the burden. Research at the U.S. Salinity Laboratory indicates irrigated agriculture can reduce its contribution by efficient irrigation that provides water of low salinity in the upper portion of the crop root zone while the salinity of the water in the lower portion can be permitted to concentrate considerably more than had previously been suspected without decreased yields. If these results hold true under field conditions, the leaching requirement of most crops grown with Colorado River water could be reduced below 10%. Lower leaching requirements, if achieved, would also reduce salt discharge to the river due to precipitation of lime and gypsum in the soil and because of decreased salt pickup from saline underground sources.

To evaluate the minimum leaching concept for alleviating the salinity problem of a major river basin, two field studies have been initiated in the Wellton-Mohawk Irrigation and Drainage District of southwestern Arizona. The first field experiment was installed in December 1973 in citrus on coarse-textured, mesa soil, and the second was started in September 1974 in alfalfa on fine-textured, valley soil.

The paper will describe the experimental design of both experiments and initial data on crop water use, soil salinity profiles, and leaching fractions achieved will be presented.

INTRODUCTION

Irrigation return flow can contribute significantly to the salt loading of rivers and other water bodies. For the Colorado River, EPA (1971) estimated that 37% of the salinity at Hoover Dam could be attributed to irrigation. But what can be done through irrigation management to reduce the salt contribution from this source?

Three distinct processes may be listed as the principal causes for increased salinity in irrigation return flows. Seepage water (and to a lesser degree tail water) may dissolve salts from the soil or underlying saline strata; seepage water may displace groundwater of higher mineral content; and evapotranspiration always reduces the volume of water that carries the salts, thereby increasing the concentration. To the extent that seepage water dissolves salt or displaces salt water, reductions in the seepage from canals, laterals and drains will reduce salinity downstream. Here we restrict the discussion to the effects of changing the deep percolation on cropped fields.

Research has demonstrated how both the amount and the composition of salt dissolved in the drainage water leaving the rootzone of a crop can be varied by changing the leaching fraction (Rhoades *et al.*, 1973). At high leaching fractions, *i.e.*, when a large part of the irrigation water applied passes through the rootzone, water tends to dissolve salts from the soil minerals at low leaching fractions, some salt species tend to precipitate. As the leaching fraction is reduced, by improved irrigation management, the situation favoring dissolution gradually shifts to one favoring precipitation. Consequently, the total salts carried by the drainage water are decreased. The quantities involved vary with the situation, but they can be substantial.

Also, Bernstein and Francois (1973) showed the alfalfa could be irrigated with a far lower

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leaching fraction than previously thought without significant yield reductions. They postulated that, as long as water of low salinity was freely available to the plant roots at shallow depths, the roots in the lower part of the rootzone could concentrate the soil solution to a maximum value that could be determined by extrapolating a plot of relative crop yield *vs.* soil water salinity to zero yield. This interpretation results in required minimum leaching fractions of about 1/3 to 1/4 those generally recommended.

Combining the above findings with considerations from soil physics concerning water flow in soils, we proposed (van Schilfgaarde *et al.*, 1974) that irrigation management practices could be divised that would increase irrigation efficiency and thereby reduce substantially the amount of salt in the drainage water. Two field experiments were initiated to test this hypothesis. This paper gives a progress report on these field studies. More detailed information may be found in USSL Staff (1977) and Hoffman *et al.* (1977).

The Setting

The experiments were established in the Wellton-Mohawk Irrigation and Drainage District of Arizona. The District contains about 26,000 ha of irrigated lands along the Gila River. Roughly 4,000 ha are on a coarse-textured mesa that rises about 20 m above the flood plain; the remainder is on the flood plain. The valley, roughly 6 km wide and 65 km long, is underlain by a gravel aquifer. On the east, it is bounded by the Mohawk Mountains. On the west, the Gila Mountains severely restrict subsurface drainage. The irrigation water is diverted from the Colorado River at Imperial Dam, lifted 52 m, and distributed through lined canals. Some 108 drainage wells pump into a lined drainage canal. In recent years, the drainage rate has averaged about 8500 l/s (2.7×10^8 m^3/yr or 210,000 AF/yr) and in 1972 the salinity of these flows averaged 3700 mg/l. The drainage water can be returned to the Colorado River either above or below Morelos Dam, the point of diversion for irrigation in Mexico. Since this drainage volume (2.7×10^8 m^3) makes up about 16% of the amount delivered annually to Mexico by treaty (1.7×10^9 m^3), mixing it with the water detained behind Morelos Dam significantly affects the salt concentration of irrigation water in the Mexicali Valley; discharging it downstream from Morelos Dam increases the volume of water that must be released at Imperial Dam to satisfy treaty obligations.

Objectives

The primary objective of the field studies is to determine the feasibility of reducing the salt output in drain water by reducing leaching without reducing crop yields, through uniform and frequent irrigations. Additional objectives are to determine the components of the water and salt balance quantitatively and to establish requirements for irrigation systems to achieve low leaching under field conditions.

EXPERIMENTAL PROCEDURE

Citrus

The first experiment was established in December 1973. It utilized nearly 2 ha of Valencia orange trees (Citrus senensis L.) centered within a 4-ha block planted in the fall of 1973. It is located on the mesa, 3 km east of Tacna, Arizona, on the Desert Valencia Ranch. The experiment is surrounded by trees of similar age, except on the south, where it is bordered by the Mohawk Irrigation Canal. The 4-ha block was chosen because of its history of high yield, and the experimental site was located within the block on the basis of the uniformity of tree trunk circumference. The tree spacing is 4.9 × 6.7 m and the dripline of a typical tree is 4.5 m in diameter. The randomized block experiment consists of 5, 10, and 20% leaching treatments replicated nine times, using 3- by 3-tree plots (Fig. 1). This design should detect 12% yield differences at the 5 % confidence level (Jones, Embleton, and Cree, 1957). The experiment is separated from the remainder to the flood-irrigated grove by border trees irrigated to achieve 20% leaching. Frost protection and tree pruning management is the same as for the surrounding groves.

The soil, a Dateland fine-sandy loam soil (Typic, Haplargid, couarse laomy, mixed hyperthermic), is calcareous throughout, well-drained, moderately permeable, and representative of the soils where citrus is grown in the District. It is underlain with sand beginning at a depth of 1.5 to 2.0 m and continuing to at least 2 m.

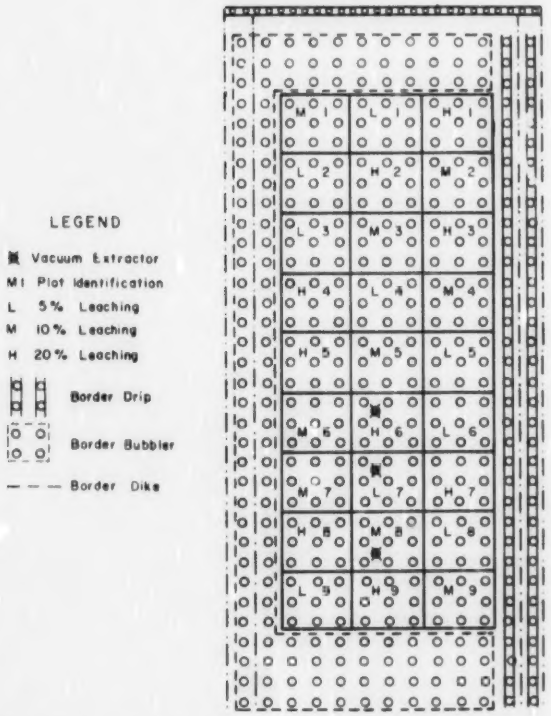
LEGEND
Vacuum Extractor
M1 Plot Identification
L 5% Leaching
M 10% Leaching
H 20% Leaching
Border Drip
Border Bubbler
Border Dike

Figure. 1 Design of minimum leaching experiment on mature Valencia orange trees in southwestern Arizona.

Irrigation water is continuously available in the Mohawk Canal. A typical concentration of total dissolved solutes in the irrigation water during 1975 was 944 mg/l; the major salt constituents and their concentrations were (in meq/liter) Ca, 4.5; Mg, 2.7; Na, 6.8; HCO_3, 2.8; SO_4, 7.7, and Cl, 3.5. Water for the experiment is pumped directly from the canal, passed through commercial sand and screen filters, and delivered in buried, plastic mains to each plot. The filters remove foreign material larger than 75 micrometers in diameter. The 11-kW centrifugal irrigation pump can deliver 16 l/s at a pressure of 350 kPa.

The frequency and duration of irrigation are controlled by programmable time clocks, which operate the pump, and by automatic irrigation controls, which operate electric valves at each plot. The time clock for the experimental plots is programmed to operate the pump for 30 min as many as three (winter) to six (summer) times every day. A flow control valve at each tree delivers 32 ml/sec or 57 liters to each tree in a plot receiving water that irrigation period; this is equivalent to a uniform surface application of 1.7 mm over the entire area. The volume of water applied to each plot is measured by two water meters placed in series to insure accurate, fail-safe measurements. Each of the 243 experimental trees is irrigated with a 35-m spiral of dual-chamber drip irrigation tubing as shown in Fig. 2. The tubing has 0.5-mm diameter outlets every 0.3 m along its length. This design was chosen to provide uniform water application under each tree. The border trees are irrigated by a second programmable time clock that operates the pump and automatic irrigation controls for 45 min as many as two (winter) to four (summer) times every day when the experimental plots are not being irrigated. Some of the border trees are irrigated bubblers filling small basins formed under each tree at a controlled rate of 63 ml/sec. Other border trees are drip irrigated from capillary tube emitters (1.7 mm ID) inserted into 25-mm-diameter polyethylene pipe laid on the soil surface about 1 m from the trunk on both sides of each tree row. The emitters are spaced 0.7 m apart, giving 14 per tree. Flow control valves in each pipeline deliver an average of 32 ml/sec to each tree. The three irrigation systems are illustrated in Fig. 3.

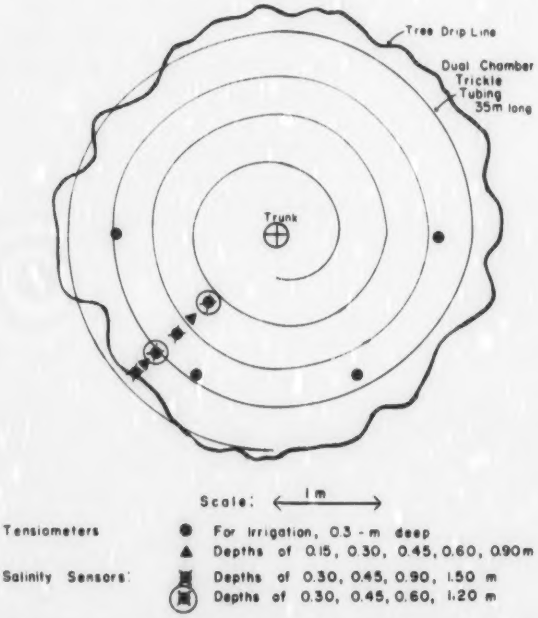
Tree Drip Line
Dual Chamber Trickle Tubing 35m long
Trunk
Scale: 1 m
Tensiometers
● For irrigation, 0.3 - m deep
▲ Depths of 0.15, 0.30, 0.45, 0.60, 0.90m
Salinity Sensors:
Depths of 0.30, 0.45, 0.90, 1.50 m
Depths of 0.30, 0.45, 0.60, 1.20 m

Figure. 2 Illustration of instrumentation under center tree of three of the nine replications for each leaching treatment. The remaining replications have two sets of salinity sensors and one set of tensiometers.

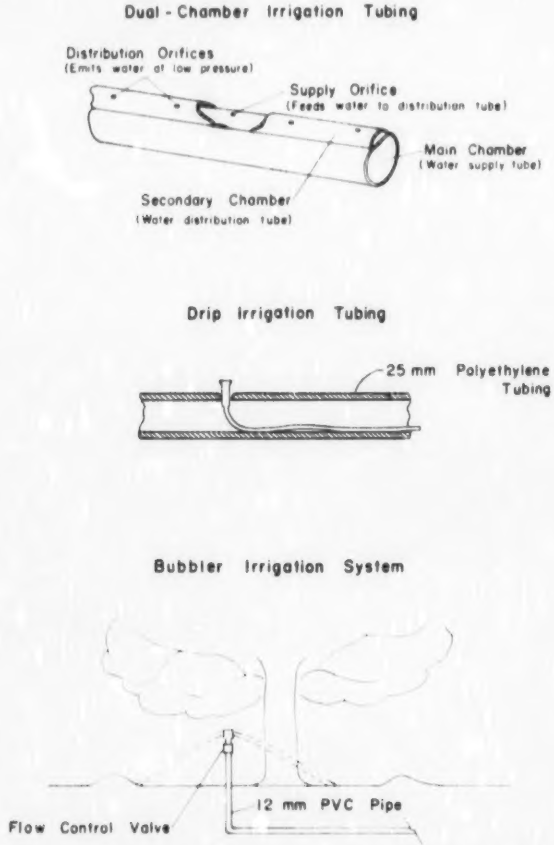
Dual - Chamber Irrigation Tubing
Distribution Orifices
(Emits water at low pressure)
Supply Orifice
(Feeds water to distribution tube)
Main Chamber
(Water supply tube)
Secondary Chamber
(Water distribution tube)
Drip Irrigation Tubing
25 mm Polyethylene Tubing
Bubbler Irrigation System
12 mm PVC Pipe
Flow Control Valve

Figure. 3 Sketch of dual-chamber, bubbler, and drip irrigation systems.

Each plot is irrigated automatically by signals generated at four tensiometers installed at the 0.3-m depth and located 60 degrees apart and 1.5 m radially out from the trunk of the center tree of each plot (Fig. 2). The signal is generated by a light-emitting diode and a phototransistor placed directly opposite each other on the manometer columns of the tensiometers (Austin and Rawlins, 1977). As the soil dries, rising mercury in the manometer column interrupts the light beam from the diode. When a signal is received from two or more of the four tensiometers, a circuit is triggered that opens a solenoid valve to irrigate the plot for 30 min. The soil matric potential at which irrigation occurs is controlled by setting the elevation of the phototransistors on the manometer column. Lowering the setpoint raises the soil matric potential and increases leaching; raising the setpont decreases leaching. Soil salinity measurements made with in situ sensors (Richards, 1966; Oster and Willardson, 1971) at the 0.30- and 0.45-m depth serve as feedback to the tensiometer-controlled irrigation system. To achieve the desired leaching, the tensiometer setpoints are adjusted based upon the difference between measured salinity and that predicted from the soil water composition model of Oster and Rhoades (1975). The predicted salinity depends on the chemical composition of the irrigation water, the partial pressure of CP_2 in the soil, and the soil water uptake distribution of the crop, as well as the leaching fraction. For purposes of control, the border trees are treated as two plots. Their setpoints are adjusted so that the total amount of water applied approximately equals that for the 20% leaching plots.

Additional tensiometers and salinity sensors, in two spatial distributions, were installed beneath the center tree of each plot. For three of the nine replications of each leaching treatment, for sets of salinity sensors and two sets of tensiometers were installed along one radial (see Fig. 2). For the remaining six replications, only two sets of salinity sensors and one set of tensiometers were installed. The salinity sensors and tensiometers are read twice weekly.

Four vacuum extractors (Duke and Haise, 1973) were installed in one replication of each of the three leaching treatments to measure the volume and chemical composition of the soil solution leaching below the undisturbed root zone. The location of the extractors is shown in Fig. 1. Each extractor within a treatment is located on a line directed toward the center of four different trees from a common manhole at a depth of 1.2 m. A diagram of the extractor for one tree is given in Fig. 4. Each extractor consists of three soil-filled sheet-metal troughs (0.15 m wide by 0.20 m high by 0.61 m long), each containing two lines of ceramic tubes (12 mm in dia.) at the bottom. Soil solution is drawn through each set of these tubes to a bottle held under partial vacuum. The vacuum is adjusted so that two tensiometers installed over the center of the extractor read the same as two tensiometers about 0.3 m away from the extractor at the same depth (see inset in Fig. 4). With uniform soil matric potential near the top of the extractors, they should intercept the flux representative of their cross-sectional area without causing convergence or divergence of flow.

The citrus grove around the experimental site is irrigated by ranch personnel by border

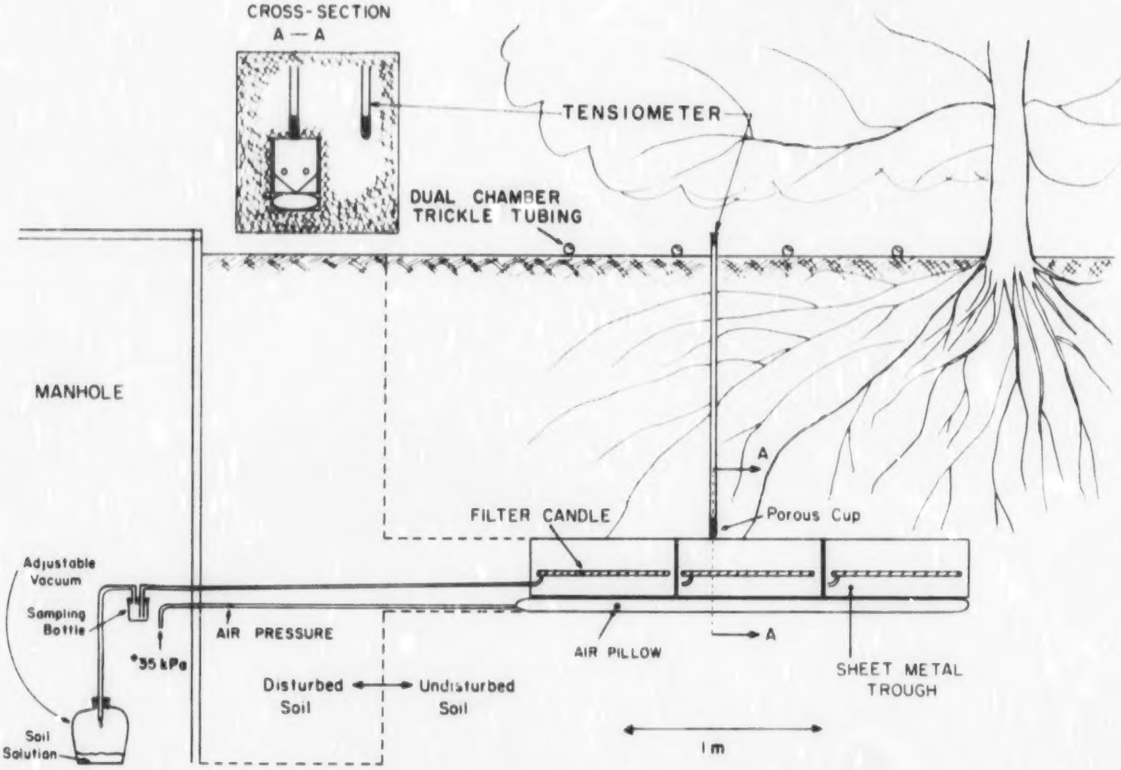

Figure. 4. Schematic of vacuum extractor installation.

flooding; a border consists of 6 rows of 35 trees each, a total area of 0.7 ha, surrounded by earthen dikes. A typical border is irrigated to a depth of 150 mm in about 45 min through six sliding gates in the wall of a concrete irrigation lateral. One border in the 4-ha block of trees immediately north of the experiment was selected for comparing fruit yield and quality, trunk growth, and irrigation volume with the experimental plots. Soil matric potential is monitored with tensiometers, as described above, under three separate trees. Because of the high leaching percentage in the border, the soil salinity level is low and is monitored periodically from soil samples. Water applied to this border is measured with a concrete, critical-flow flume (Replogle, 1977) installed in the irrigation lateral. The irrigation volume can be calculated to within about 2% from the irrigation period and a continuous record of the water elevation at the entrance relative to the flume floor at its throat.

The experimental trees are fertilized by foliar applications of urea and microelement chelates instead of through the irrigation as is done in the surrounding groves. One border of flood-irrigated trees east of the experiment and within the same 4-ha block is fertilized similarly to serve as a fertilizer check for fruit yield and quality and trunk growth with the experimental trees.

The fruit from all the experimental trees, the two rows of border trees on the east and west, and three rows of trees from both the flood- and fertilizer-check plots are harvested by individual tree in April of each year and weighed. Some fruit is selected for quality determinations. Trunk circumference is measured annually as a simple measure of tree growth.

Alfalfa

The second experiment is 13 km northeast of Tacna, Arizona, on the Snyder Ranch in the flood plain of the Gila River. The experimental site is the northern quarter of an 8-ha field that had been previously cropped to alfalfa and flood irrigated. Within 400 m of the south end of the field, the topography rises 20 m to the mesa where citrus is grown. A drainage well for water-table control is located next to the southwest corner of the field. The experimental site was instrumented and the irrigation system installed during September 1974. After cultivation, alfalfa (*Medicago sativa* L., cv. Hayden) was planted early in October.

The Indio fine-sandy loam soil (Typic Torifluvent, coarse silty, mixed hyperthermic), representative of the valley soils in the district, is calcareous and will drained. The soil profile texture grades from very fine sandy loam to silt loam at a depth of 0.3 m and to silty clay loam at a depth of 0.8 m.

The experimental design, shown in Fig. 5, consists of three leaching treatments, 5, 10, and 20%, each replicated five times. Each plot is 12.2 m wide and 104 m long. The remainder of the 8-ha field is irrigated by the rancher using level-basin flooding.

The irrigation water, pump, and filter system are identical to those for the citrus. Water is applied with an electrically driven, lateral-move irrigation system 195 m long with wheel towers 12.2 m apart. As in the citrus experiments, water for each plot passes through two water meters in series and then through 20 spray nozzles (Fig. 6). At a pressure of 70 kPa, each nozzle delivers 30 ml/sec. At a ground speed of 30 m/hr, the irrigation system applies about 6 mm each pass. The number of passes varies from one every few days in winter to a maximum of two passes per day in summer. The differential leaching treatments are achieved by regulating the pressure for each plot with a throttle valve.

Two replications of each leaching treatment were instrumented. A concrete manhole was installed at the border between adjacent plots for the six replications instrumented (Fig. 7). After excavating for the manhole, two vacuum extractors, each 1.5 m long, were installed at the 1.2-m depth in each of the six instrumented plots. The vacuum and pressure

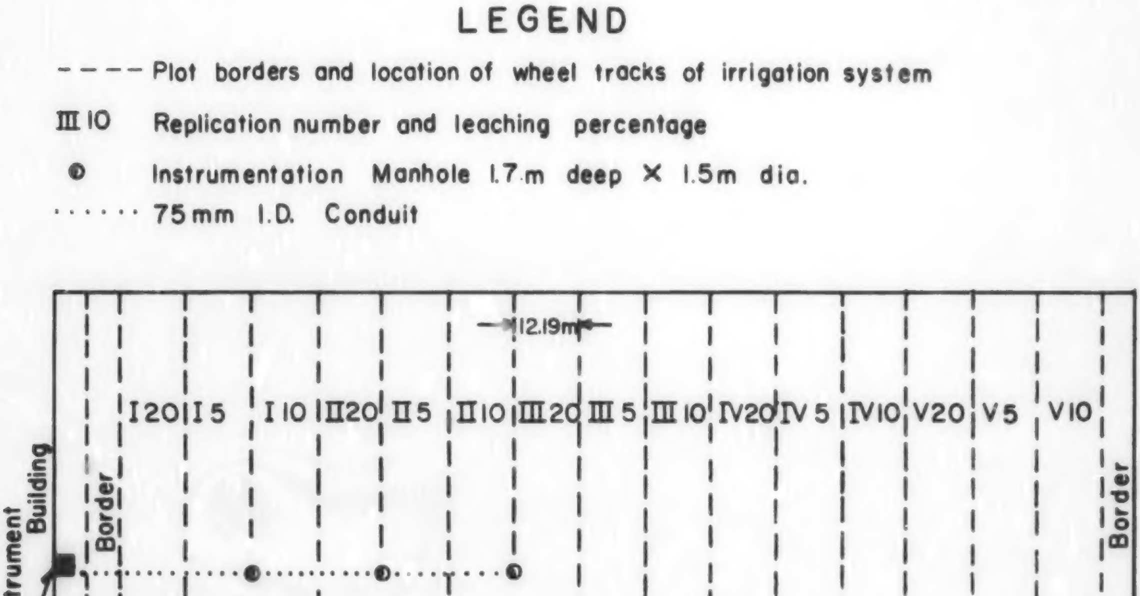
LEGEND
---- Plot borders and location of wheel tracks of irrigation system
III 10 Replication number and leaching percentage
● Instrumentation Manhole 1.7 m deep × 1.5m dia.
······ 75 mm I.D. Conduit
12.19m
I 20
I 5
I 10
II 20
II 5
II 10
III 20
III 5
III 10
IV 20
IV 5
IV 10
V 20
V 5
V 10
Instrument Building
Border
Border

Figure. 5 Design of minimum leaching experiment for alfalfa in southwestern Arizona.

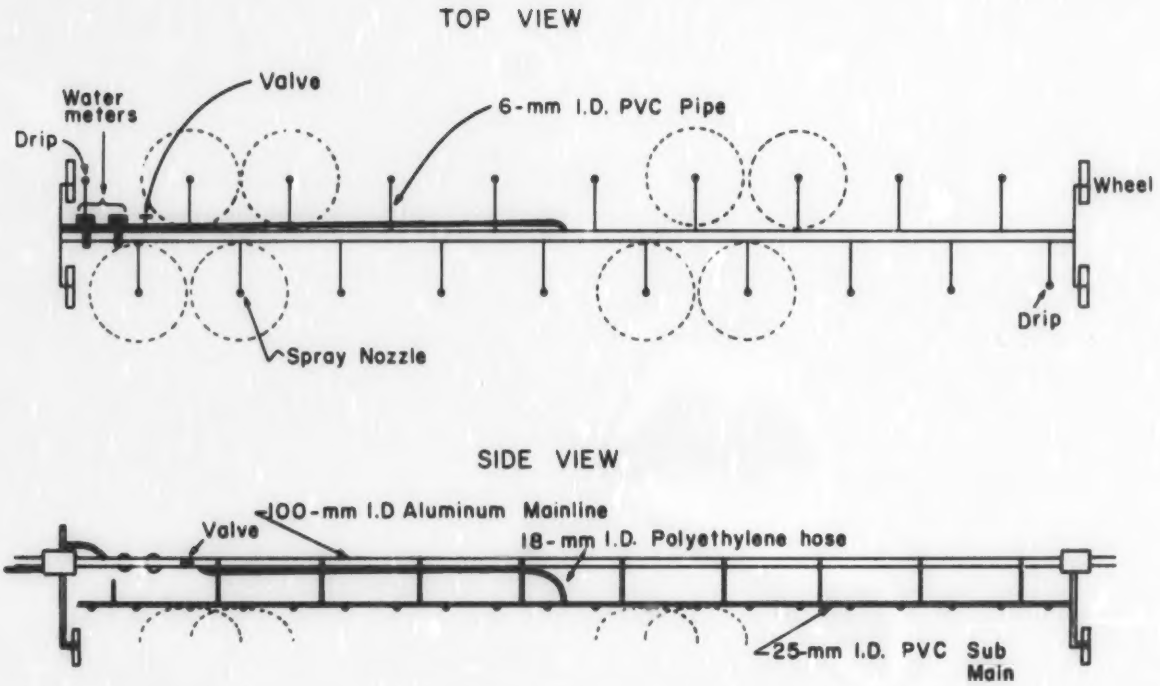
TOP VIEW
Valve
Water meters
Drip
6-mm I.D. PVC Pipe
Wheel
Drip
Spray Nozzle
SIDE VIEW
100-mm I.D Aluminum Mainline
Valve
18-mm I.D. Polyethylene hose
25-mm I.D. PVC Sub Main

Figure. 6 Spray system for one section of the lateral move irrigation system serving one replication.

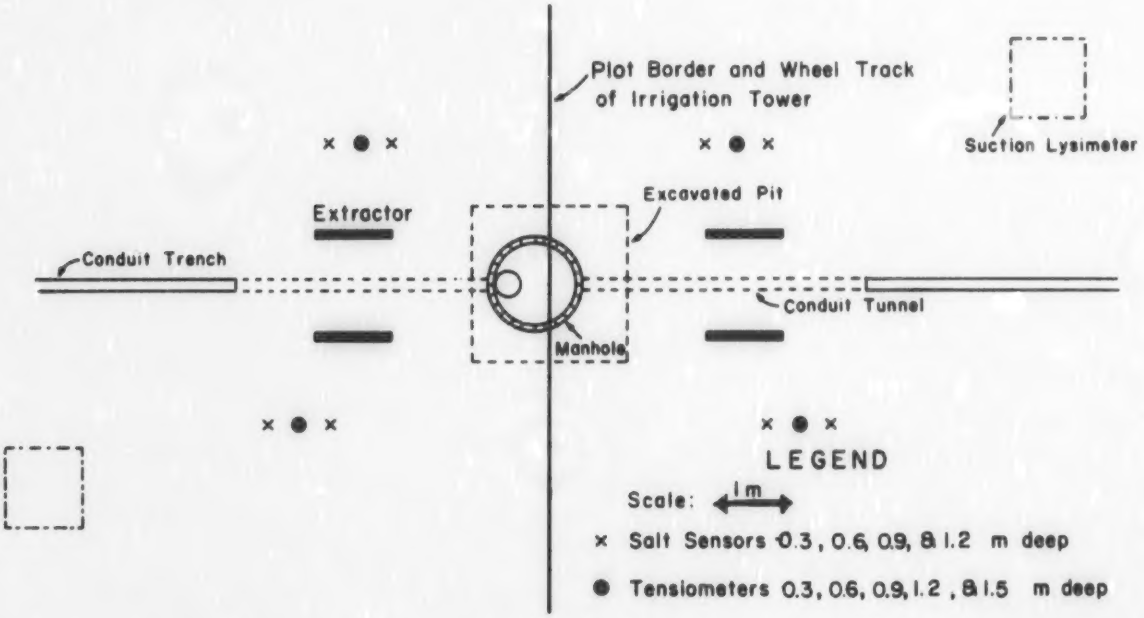
Plot Border and Wheel Track of Irrigation Tower
Suction Lysimeter
Excavated Pit
Extractor
Conduit Trench
Conduit Tunnel
Manhole
LEGEND
Scale: 1m
× Salt Sensors 0.3, 0.6, 0.9, & 1.2 m deep
● Tensiometers 0.3, 0.6, 0.9, 1.2, & 1.5 m deep

Figure. 7 Location of instruments for two of the six replications instrumented in the alfalfa experiment.

lines to the extractors were installed through an underground conduit to each manhole. Salinity sensors and tensiometers were installed as shown in Fig. 7. In addition to the vacuum extractors, a 1.2-m-deep suction lysimeter was installed in each of the six instrumented plots. These were formed by lining a 1.5-m-square hole with 250-μm-thick plastic film. A wooden frame, 0.3 m below the soil surface, serves as the top lip of the lysimeter. After backfilling with about 0.1 m of soil, ceramic tubes, identical to those used in the vacuum extractors, were installed in each lysimeter to extract the leachate. The extractors were then filled with disturbed soil and compacted by saturating with water.

The portion of the 8-ha field not within the experiment, which serves as the check plot, is flood irrigated as a level-basin from a single gate located in one corner of the field. For each irrigation, a depth of about 150 mm is applied at the rate of about 0.4 m^3/s. Irrigation volume is measured with a critical-flow flume identical to that used in the citrus experiment. Salinity sensors were installed at four depths in six locations in the check plot.

All of the crop management practices, including planting, harvesting, and pest and weed control, are performed by personnel of the Snyder Ranch. The alfalfa is harvested by cutting with a windrower conditioner and cubing, following customary procedures. Harvest dates are chosen by the ranch when the alfalfa is at approximately 50% bloom

The yield of each cutting is determined by weighing three samples from each replicate. Each sample is taken from a 26.8-m^2 area in the first swath (4.4 m wide) made down the center of each plot. Nine similar samples are taken from the flood check.

RESULTS AND DISCUSSION

The results presented here are illustrative rather than complete. Furthermore, they represent an interim rather than a final report. Since the initiation of the citrus study, three harvests have been made. The first harvest, in April 1974, no doubt reflected the irrigation management before the experiment began. Citrus yields tend to vary greatly and often show an alternate year pattern (Jones *et al.*, 1957, Parker and Batchelder, 1932). Also, Bingham *et al.* (1974) found that the effects on yield due to a change in irrigation management were not noted till the fourth year; and Raats (1975) predicted that a period of many months, depending on leaching fraction, would be required before a new quasi-steady-state would be reached. Thus it would be unrealistic to expect definite results in 1976. For similar reasons, the time since initiating the alfalfa experiment has been too short for definitive results. In addition, some difficulties were encountered in that experiment.

Citrus

Soil Properties

At the beginning of the experiment, extensive soil samples were collected for detailed analysis. The soil in the grove was far from uniform, with wide changes in texture from place to place; similarly, the chemical properties showed considerable variation. Table 1 gives representative values for a number of properties. The relation between hydraulic conductivity and matric potential, determined on three 0.9-m-long undisturbed cores, is given in Fig. 8.

TABLE 1

Representative Soil Properties of Dateland Fine Sandy Loam Soil

Property	*Unit*	*Typical Values*	*Range*
Cation exchange capacity	meq/100g	9-13	2.5-23
Exchangeable sodium percentage	%	3-4	3-13
Sodium adsorption ratio	—		
Saturation percentage	g/g × 100	25-30	19-50
Field water content	g/g × 100	11-12	4-22
Electrical conductivity	S/m@25	0.13-0.15	0.1-0.6
pH	—	7.4	6.4-8.3
Soluble* calcium	meq/1	3-4	1.6-23
Soluble* magnesium	"	2	0.7-11
Soluble* sodium	"	5-7	3-37
Soluble* potassium	"	0.2	tr-0.6
Soluble* bicarbonate	"	2	0.8-4.6
Soluble* sulfate	"	5-6	2.3-56
Soluble* chloride	"	2-3	0.9-28
Soluble* nitrate	"	0.6	0.2-6.2

*Soluble in saturation extract.

Water Use

Annual totals of water applied are given in Table 2. When analyzed on a month-to-month basis, the data show that the application rates by treatments were not always in the expected order; the totals, however, were ordered as expected. Monthly averages show a range from 1 mm / day (3.27 l / tree-day) to 11 mm / day (360 l / tree-day), if an inadvertent overirrigation in one month (July 1976) on the 20% leaching plots is not considered.

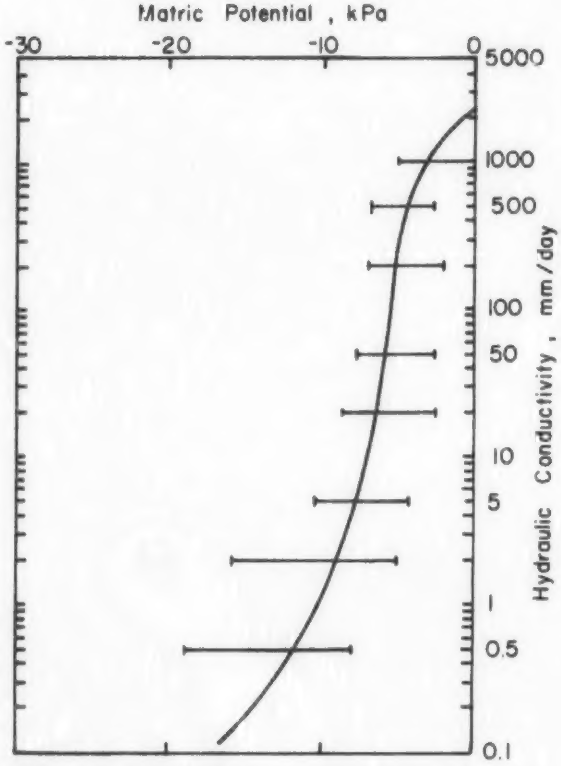

Figure. 8 Relationship between soil matric potential and hydraulic conductivity for Dateland fine sandy loam soil.

TABLE 2

Annual Irrigation, Rainfall, and Pan Evaporation for Citrus

	Depth of water applied*								
	Leaching Treatment			Borders		Flood	Rain-	Pan Evap-	Cal-culated
Year	5%	10%	20%	Bubbler	Drip	Check	fall	oration	ET
	mm								
1974	1401	1450	1685	1651	1818	–	105	1838	1328
1975	1498	1560	1802	1942	1912	2582	84	1732	1423
1976†	1675	1725	1975	2049	1704	2750	90	1650	1550
Average	1525	1578	1821	1881	1811	2666	93	1740	1434

*Irrigation plus rainfall.

†Data estimated for October, November, and December.

The 3-year average water applications support, but by no means prove, the hypothesis that the desired leaching fractions were closely approximated. Using that assumption, one can calculate an average annual evapotranspiration rate (ET) of 1440 mm. Application of that estimate of ET to the flood check water use, yields an estimated leaching percentage of 46%. ET was 83% of pan evaporation, as measured with a pan placed within a nearby citrus grove in a space cleared by removing one tree. Referred to a pan some 5 km away in an open area, the pan factor was 0.71.

Clearly, the above calculations and assumptions are somewhat tenuous. Reliable, direct measurements of ET are not available, and the direct measurements of leaching volumes are also considered unreliable. However, some additional information should be considered. In 1974, water was purposely withheld to increase the salinity to the projected levels; thus, some of the water used was from soil storage. As experience was gained, it became evident that the imposed changes in water application rates lagged the changes in pan evaporation. In 1976, in an effort to compensate for this lag, we overirrigated for a period. These two sets of events qualitatively explain some of the year-to-year differences shown in Table 2.

Comparisons were also made with ET estimates calculated from climatological data using the modified Penman (Doorenbos and Pruitt, 1975) and Jensen-Haise (Jensen, 1973) equations and with the data published by Erie *et al.* (1965). These comparisons led to the following values for yearly evapotranspiration in mm:

Erie	1000
Jensen-Haise	1342
Penman	1421
Field estimate	1440

The citrus data reported by Erie *et al.* were taken from earlier work where the water use was determined gravimetrically, but the water lost from the top 0.15 m was ignored (Jensen, M. E., personal communication, 1975). Thus one would expect them to give an underestimate.

Soil Water Potential

The tensiometer readings give an indication of the water potential distribution in the rootzone of the trees. The average profiles for the three leaching treatments during 1974 and 1975 (Fig. 9) show that the soil was indeed substantially drier at depths below 0.6 m for the plots with 5% leaching than at 20% leaching. Near the surface, the potentials were essentially the same. Average profiles, however, do not reflect the details of the flow regimes, nor do they bring out the heterogeneity in the system.

To better understand the detailed flow patterns, we installed 84 additional tensiometers under the center tree in plot H4 (Fig. 1)

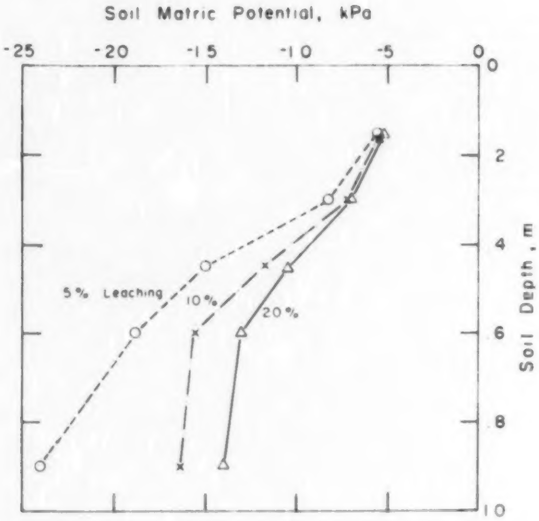

Figure. 9 Average soil matric potential profiles for the three leaching treatments in the citrus during 1974 and 1975.

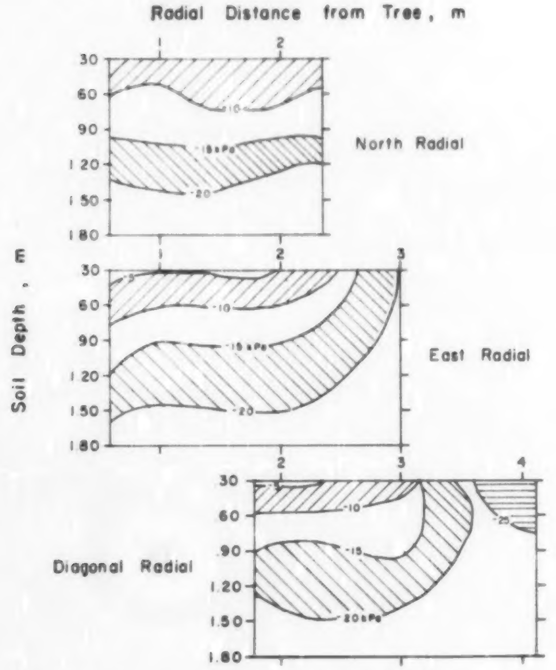

Figure. 10 Distribution of total head under the center citrus tree of plot H4 in the evening on August 29, 1976.

in three planes through the tree trunk and read them frequently. Figures 10, 11, and 12 illustrate some of the trends. They represent total head distributions referred to the 0.3-m depth as datum for August 24, August 29, and September

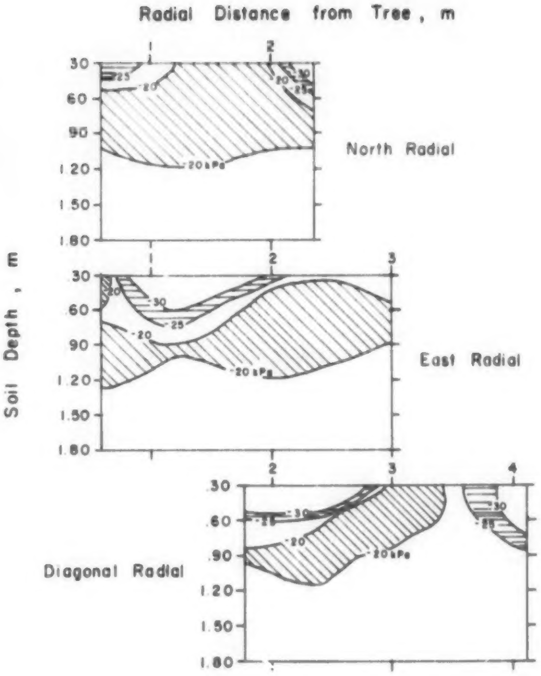

Figure. 11 Distribution of total head under the center citrus tree of plot H4 in the evening on August 29, 1976.

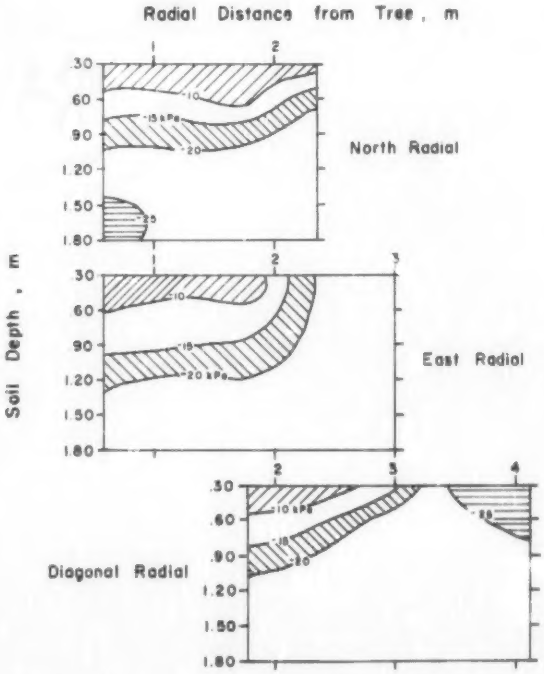

Figure. 12 Distribution of total head under the center citrus tree of plot H4 on September 4, 1976.

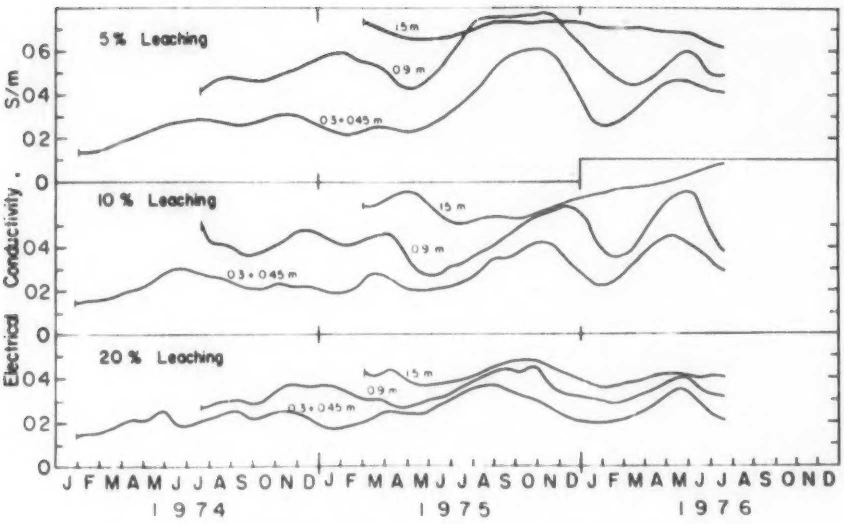

Figure. 13 Salinity trends with time for the three leaching treatments of the citrus experiment.

4, 1976. On August 24, irrigation had reasonably met crop demand, but that morning the irrigation water was shut off and left off until 2040 hours on August 29. The setpoint (i.e., the control point for irrigation at 0.3 m) during this period was -5.5 kPa.

The data illustrate that the flow patterns clearly were not one-dimensional. The head at the 0.3-m depth was controlled by the setpoint when the irrigation system was operating. The 6-day drying period is reflected in the substantially drier profile on August 29. By September 4, the distribution again resembled that of August 24 very closely. The direction of the gradients strongly suggests there is little root activity below 0.6 m.

Soil Salinity

The time course of average soil salinity measured with salinity sensors is given in Fig. 13 for the three leaching treatments. (Salinity data for the 0.6- and 1.2-m soil depths are not given to simplify the figure.) Initial soil-salinity levels were about equal to the salinity of the irrigation water, 0.13 S/m, because of overirrigation before the experiment. Beginning in February 1974, soil salinity increased with time until quasi-stable values were attained at the 0.3- to 0.45-m depth by July (5 months) and at the 0.9-m depth by January 1975 (11 months). Since March 1975, changes in soil salinity have undergone two complete cycles. The cyclic pattern is evident to a soil depth of 0.9 m and the cycle takes about 1 year. During the first half of the year, the trees were underirrigated and soil salinity increased; during the last half of the year, the trees were overirrigated and salinity decreased. Although cyclic, the differences in salinity among leaching treatments were as expected, with 5% leaching being the most saline and 20% leaching the least.

Figure 14 compares time-averaged soil salinity as a function of soil depth for the intervals of January 1974 to July 1975 and July 1975 to July 1976, the initial soil-salinity distribution, and the projected soil-salinity distribution at equilibrium from the model of Oster and Rhoades (1975). In general, soil salinity increased with time at all soil depths and salinity decreased with increasing leaching. The soil-salinity distribution has reached the projected salinity values for all three leaching treatments to a depth of 1.5 m, except at the deeper depths in the 5% leaching treatment.

Water Uptake Distribution

Of interest are the distribution of water uptake with depth and the changes in salinity with depth over time. From extensive soil sampling, chloride distributions have been obtained at various times under selected trees. Oster (this conference) will discuss these in detail. Here we only point out that, with some difficulty, such data can be used to estimate the water uptake distribution. In Table 3, we present the results of such calculations for one tree irrigated with a

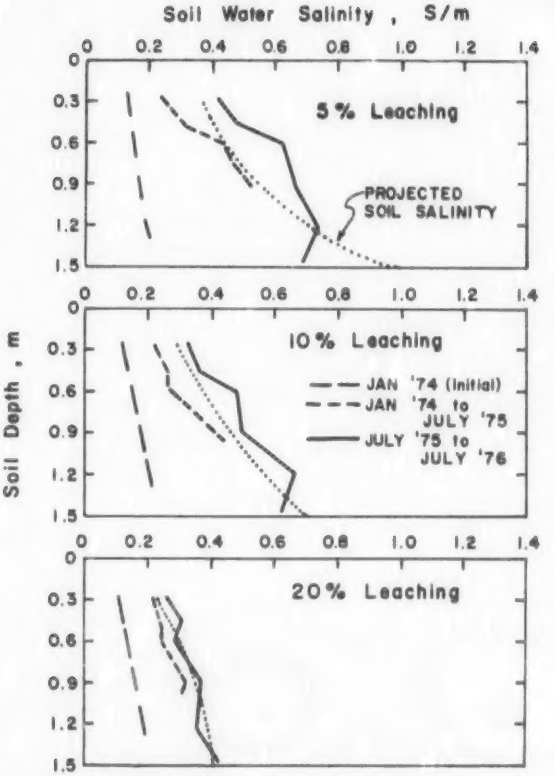

Figure. 14 Time-averaged soil salinity distributions with soil depth at initiation, for two intermediate time periods, and the projected final conditions.

leaching fraction targeted at 0.20 and one, at 0.05. From weighted chloride data, the actual LF's were estimated to have been 0.30 and 0.06.Irrigation water was taken as containing 3.3 meq/l of chlorides

Raats (1975) has indicated how the travel time for a parcel of water through the soil profile can be calculated if the uptake distribution is known. For purposes of generalization, he assumed an uptake distribution of the form

$$\beta = \delta^{-1} \exp(-z/\delta),$$

where β is the fraction of the total water taken up above depth z and δ may be interpreted as a characteristic rooting depth. When $z = \delta$, 63% of the water uptake has taken place. Figure 15 shows such travel times for three leaching fractions, assuming δ = 0.2m and δ = 0.4m. When the data in Table 3 are used, the paralled calculations give results very close to those for δ = 0.4. These curves may be interpreted in terms of the time required to establish a new equilibrium after irrigation management has changed. We conclude that we should expect to establish a new quasi-equilibrium no sooner than 9 months after initiation of a 5% leaching treatment at a depth of 1.8 m, and no sooner than 3 months for 20% leaching. These estimates are of the right order of magnitude, but somewhat shorter than suggested in Fig. 13.

TABLE 3

Chloride and Water Uptake Distribution Under the Center Trees of a High and a Low Leaching Plot

	Plot H4		*Plot L7*	
Soil Depth	*Cl Concentration*	*Accumulated RWL**	*Concentration*	*Accumulated RWL**
m	meq/l		meq/l	
0.3	6.0	0.64	12.0	0.77
0.6	8.3	0.86	14.5	0.83
0.9	9.4	0.93	18.0	0.88
1.2	10.2	0.97	23.0	0.92
1.5	10.6	0.98	33.0	0.97
1.8	—	—	45.0	1.00

*Relative water loss (part of water consumed above depth indicated).

Vacuum Extractor Volumes and Concentrations

It was stated earlier that a reliable direct measurement of leaching volumes was not available. We had hoped that the vacuum extractors would yield such data. However, the volumes collected have been consistently too low. This result can be explained in part by mechanical failures. Restrictions due to plumbing failures and poor contact between the extractors and the undisturbed soil have recently been noted in some of the extractors and corrected. However, a more basic cause relates to nonhomogeneity of the soil profile. The extractors depend, for proper operation, on the continuity of vertical flow. When the soil texture changes from fine to coarse, such continuity is not maintained. Especially where pockets of sandy soil are imbedded in finer textured soil, theory and experiment predict that unsaturated flow will tend to bypass the coarse-textured pockets. Field observation has verified that this situation indeed occurs for at least some of the extractor segments.

The extractor leachates have been analyzed chemically. The leaching fractions calculated from the chloride levels were 0.06, 0.15 and 0.27 for the low, medium and high plots, respectively. These values are reasonable and approximately the same as determined by alternate methods. From early data, it is estimated that the LF prior to initiating the experiment

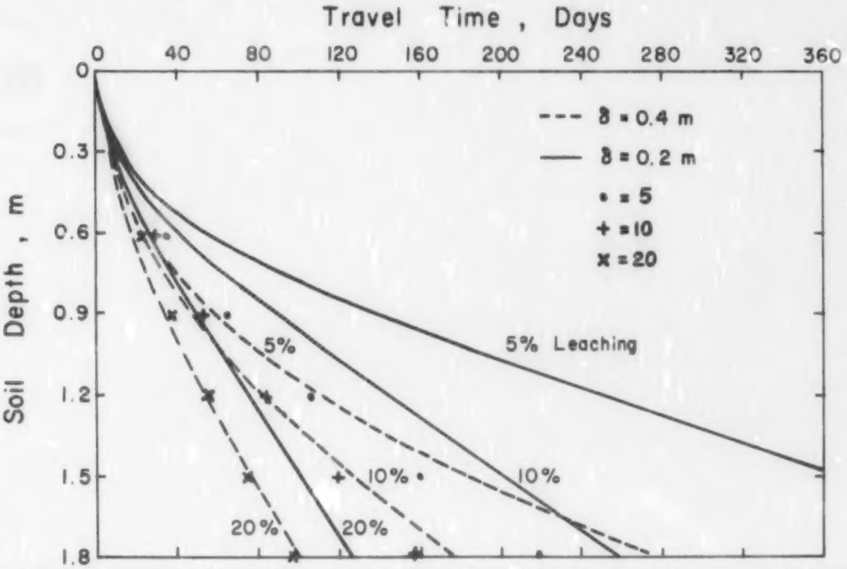

Figure. 15 Chloride-derived and calculated travel time for a parcel of water to pass through the soil profile as a function of leaching fraction and rooting depth. The curves are calculated from Raat's theory with $\theta = 0.15$ and ET = 7mm/day. The plotted points are derived from the chloride data (Table 3) for the leaching percentages indicated.

was at least 0.33. This compares with 0.46 determined from the water use data on the check plot.

Fruit Yield and Quality

The average annual yield, regardless of treatment, was 120, 149 and 83 kg/tree for 1974, 1975 and 1976, respectively. There was no statistical difference in yield between any of the treatments, including the border and check plots. Similarly, treatments did not differ in number of fruit harvested, or in fruit quality. The drastic difference from year-to-year appears to be typical of citrus, as indicated earlier. Measurements of trunk diameter verified that the trees are continuing to grow, again without any differences attributable to treatment. In view of the findings by Bingham *et al.* (1974) that fruit yield depressions were noted the fourth year after salinization, the results to date must be interpreted with caution.

Alfalfa

Soil Properties

As for the citrus, we present some typical soil properties, Table 4, and a representative relationship between the hydraulic conductivity and matric potential (Fig. 16). The soil was nonsaline, indicating that it has been well leached in the past.

TABLE 4

Representative Soil Properties for the Snyder Ranch Alfalfa Field

Property	*Unit*	*Depth (meter)*	*Typical values*	*Range*
cation-exchange-capacity	meq/100g	0-0.6	15	10-19
		>0.6	28	25-35
exchangeable-sodium-percentage	%	0-0.6	8	5-12
		>0.6	10	5-30
sodium-adsorption-ratio	—	0-0.6	6	5- 8
		>0.6	7	5-30
saturation percentage	g/g × 100	0-0.6	40	30-45
		>0.6	50	42-60
field water content	g/g × 100	0-0.6	14	11-30
		>0.6	28	23-36
pH		0-0.6	7.4	6.9-8.2
		>0.6	7.5	7.0-7.8
electrical conductivity	S/m	0-0.3	0.25	0.15-0.50
		>0.3	0.35	0.17-1.0
soluble* calcium	meq/l	0-0.3	5	3.8-26
		>0.3	15	2-30
soluble magnesium	"	0-0.3	3	3-16
		>0.3	8	1-18
soluble sodium	"	0-0.3	12	10-27
		>0.3	20	10-60
soluble potassium	"	0-0.3	0.3	0.1-0.7
		>0.3	0.3	0.1-0.6
soluble bicarbonate	"	0-0.3	2.3	1.9-4.0
		>0.3	2.5	1.4-6.0
soluble sulfate	"	0-0.3	16	8-30
		>0.3	28	15-80
soluble chloride	"	0-0.3	5	3-10
		>0.3	10	5-30
soluble nitrate	"	0-0.3	0.6	0.2-3
		>0.3	0.3	0.1-1.7

*Soluble in saturation extract.

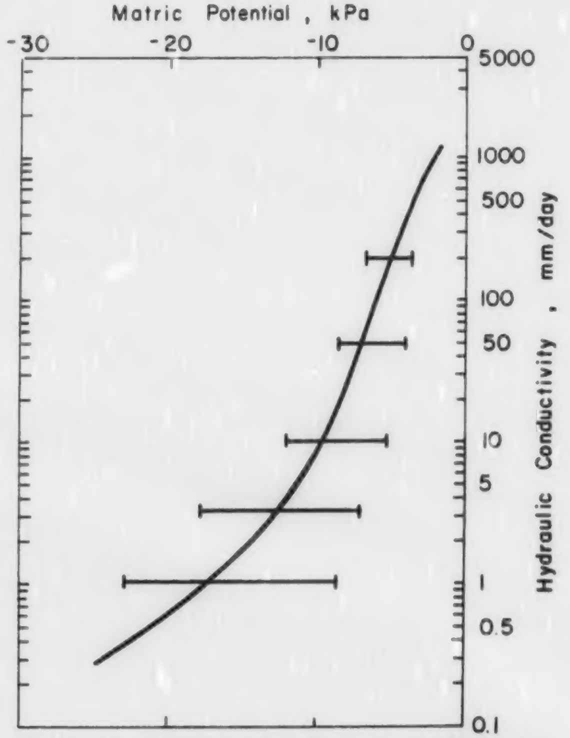

Figure. 16 Relationship between soil matric potential and hydraulic conductivity for Indio fine sandy loam.

Water Use

The total amounts of water applied from January 1975 to July 1976 were 3152, 3322, and 3613 mm for the 5, 10, and 20% leaching treatments, respectively, and 3598 mm for the flood check.

By subtracting the planned leaching depth, the total water use data can be used to arrive at an estimate of evapotranspiration. This estimate is 1813 mm/year. This compares with other estimates as follows:

Erie *et al.*	1890
Penman	2201
Brawley, Ca.	2060

The Brawley data were obtained in a weighing lysimeter (LeMert and Kaddah, 1977). Arbitrarily taking the average of these four estimates (1991 mm) as the true value, the leaching percentages for the 5, 10, and 20% leaching treatments would be -3, 2, and 10%. Other data tend to confirm that the alfalfa was indeed underirrigated.

Soil Water Potential

Tensiometric measurements have been helpful in explaining some of the anomalies noted. As illustrated in Fig. 17, the total head distributions indicated both upward and downward gradients. These and similar data may be used to draw the following conclusions. The reversal in gradient early in 1975 on the 10 and 20% leaching plots can be explained by differential water uptake with depth. Over time, these profiles developed into monotonically decreasing heads with depth, indicating that water was moving downward through the profile into the water table. In some of the 5% leaching plots, however, there was evidence of a substantial upward gradient below 0.9 m associated with water uptake from the water table. More detailed data, not shown, support the hypothesis that in some parts of the field, part of the water was supplied from the water table. Whether upward flow takes place depends not only on the irrigation management, but on localized subsoil conditions and water table position.

Soil Salinity

Initial salinity sensor measurements taken in November 1974 averaged 0.79, 0.62, 0.68, and 0.73 S/m at the 0.3-, 0.6-, 0.9- and 1.2-m depths, respectively. Due to operational difficulties with the irrigation system during the beginning of 1975, insufficient water was applied, and salinity at the 0.3-m depth increased after the experiment began, By March, salinity at the 0.3-m depth started to decrease. This decrease has continued, although short-term cycles have occurred. The lowest levels of salinity (about 0.4 S/m) were reached in January 1976 (Fig. 18). The salinity below 0.3 m was expected to increase initially, then become stable with time. Such increases did occur, with stable but high levels reached by January 1976. As shown in Fig. 19, the salinity profiles have changed from ones decreasing with depth during the first half of 1975 to ones increasing with depth during the second half of 1975. They have changed little through the first half of 1976, except for a slight increase at 0.9 and 1.2 m. These increases at greater depths show the beginning of the profile shapes expected to develop, but to date salinity has not difference significantly among treatments. For example, in May 1976, soil salinity at the 1.2-m depth was about 1.1 S/m for all leaching treatments; for irrigation water having a salinity of 0.13 S/m, the resultant leaching percentage is 12.

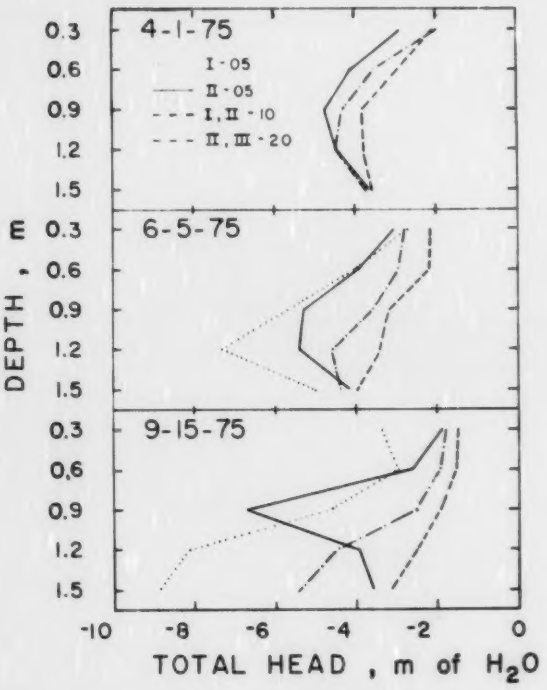

Figure. 17 Hydraulic potential distribution for the three leaching treatments in the alfalfa at selected times during 1975.

For comparison, the salinity profile for the flood check is shown in Fig. 19, along with that for the 20% leaching treatment. The salinity increased uniformly with depth, was quite stable, and was 0.2 to 0.3 S/m lower than in the experimental treatments. Based on a soil salinity of 0.77 S/m at 1.2-m depth, the apparent leaching percentage obtained on the check plot was 17%, indicating that 5% more leaching had occurred on the flood-irrigated check than on the sprinkled experimental plots.

Vacuum Extractor Volumes and Concentrations

The extractor data confirm the conclusions reached from the salt sensor, the tensiometer, and the water-use data, i.e., that the alfalfa experiment was underirrigated. The extractor volumes obtained indicate that the alfalfa was irrigated at about half the targeted leaching. The extractors in I-05 were affected by upward flow. The composition of the extractor leachates also indicated less-than-desired leaching. The compositions have not yet come to equilibrium; continuing exchange reactions account for the difference between observed and predicted compositions.

Crop Yield

The alfalfa was cut 7 times in 1975 and 5 times in 1976 through July. The 1975 yields were

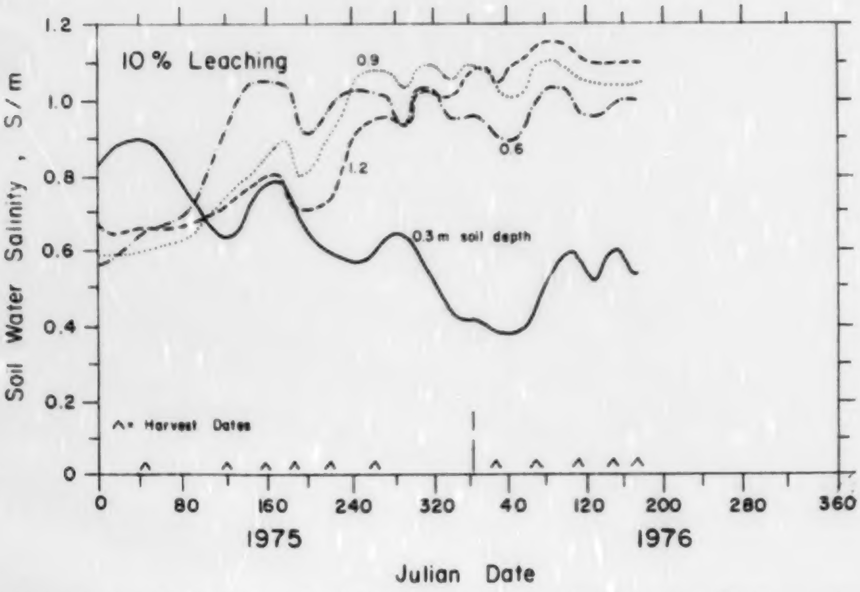

Figure. 18 Salinity trends with time for the 10% leaching treatment of the alfalfa experiment.

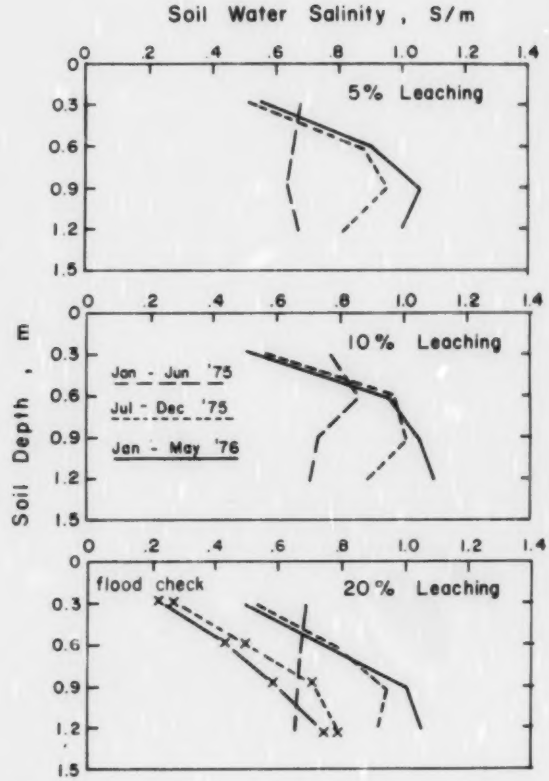

Figure. 19 Time-averaged salinity distributions with depth for three leaching treatments and the flood-irrigation check of the alfalfa experiment.

17.9, 17.6 and 17.6 Mg/ha for the 5, 10, and 20% leaching treatments; for 1976, they were 16.4, 15.8 and 15.9 Mg/ha. These yields were not statistically different with respect to treatment. The flood check yielded 21.3 Mg/ha in 1975 and 18.6 Mg/ha in 1976, 20 and 16% more than the average of the experimental plots.

These results cannot be fully explained; however, the experimental plots were plagued with excessive weeds and had a poor stand compared to the flood check. This was partly due to some problems encountered with herbicide applications and partly to the method of water application combined with the harvesting operation. The high frequency of irrigation maintained a wet soil surface that in turn resulted in a low infiltration capacity; apparently, this problem was aggravated by compaction from the frequent passage of heavy equipment for harvesting.

Some operational problems were also encountered with the irrigation equipment. As a result, during some periods more water needed to be applied than normally to make up for past deficits. Measurements of oxygen at a depth of 0.45 m indicated that, during these periods, the oxygen level in the soil air was often at 10% or below. The time-averaged salinity in the top 0.2 m of soil, for the period July 1975 to May 1976,was 0.8 S/m in the experimental plots compared to 0.5 S/m in the flood check. They yield depression expected from this 0.3 S/m difference is 12% (Maas and Hoffman, 1977).

After the July 1976 cutting, the alfalfa was removed from the field, the field was relevelled, and a new seeding established. At the same time, the irrigation system was modified to permit larger applications per irrigation. It is hoped that these changes will overcome the earlier problems.

INTERPRETATION

Experience thus far suggests that the technology is available to irrigate tree crops at controlled efficiencies to maintain the leaching percentage at 20% or less. We believe that such a management practice will not adversely affect yield or , for that matter, cost of production in the Wellton-Mohawk.

The experience with alfalfa has been less satisfactory. The irrigation method chosen to carefully control water application rates was, to some extent, incompatible with the other farming practices, and the high water table at the experimental field has compounded the results. The flood irrigated check plot, however, has indicated that a leaching fraction of around 0.10 can be maintained with conventional practices.

The consequences of these tentative conclusions may be illustrated briefly for the Wellton-Mohawk District. It should be stressed that, in different physical settings, the consequences would no doubt be different.

Let us assume the following conditions. The area (A) planted in citrus is 3000 ha; the typical water delivery using flood irrigation is 3200 mm/yr (I_p); the evapotranspiration (ET) is 1400 mm/yr; the projected average drainage water concentration in 1980 is 3000 mg/l; the irrigation water contains 944 mg/l (C_i); and the expected leaching fraction (LF) is 0.20. Then the reduction in annual volume of drainage water due to a change in irrigation management would be

$$\begin{aligned}\Delta V &= A\,\langle I_p - [ET/(1 - LF)]\,\rangle \\ &= 3000\,[3200 - (1400/0.80)\,] \\ &= 4.35 \times 10^7\ m^3/yr \\ &= 35{,}000\ AF/yr\end{aligned}$$

If we assume mass balance, without precipitation of salts in the rootzone, then the amount of salt leaving the rootzone in the drainage water would be reduced by

$$\begin{aligned}\Delta\ salt &= C_i\ \Delta V \\ &= 41{,}000\ Mg/yr \\ &= 45{,}000\ tons/yr\end{aligned}$$

However, we know that gypsum and lime will precipitate. Making that correction (Oster and Rhoades, 1975), the salt load would be reduced an additional 11%:

$$\begin{aligned}\Delta\ salt &= 45{,}100\ Mg/yr \\ &= 49{,}600\ tons/yr\end{aligned}$$

This reduction in salt input to the water table would be reflected over time in the drainage water pumped and, presumably, delivered to the proposed desalting complex. In the short run, the leaching water will displace groundwater. In 1973, the groundwater contained 3700 mg/l of salt; it has been projected to be at 3000 mg/l in 1980. Using the latter figure, the short-term effect of changing the irrigation management in the citrus would be reduction in the exported salt load of 3000 mg/l × (4.35×10^7 m^3/yr), or 130,000 Mg/yr. This compares with a current annual volume of around 26×10^7 m^3/yr containing, at 3000 mg/l, 780,000 Mg/yr.

A similar projection could be made for the approximately 8000 ha of alfalfa irrigated with an estimated leaching fraction of 0.25 in the period 1970-72

It should be emphasized that the above projections are site-specific. Under different circumstances, entirely different consequences could result. Suarez and Rhoades (1977) and Rhoades and Suarez (1976) considered a series of such circumstances and demonstrated the dependence of the results on the river water chemistry. The fact remains that irrigation management can substantially affect downstream water quality, not to mention water and energy conservation. The understanding gained from studies such as reported here, and the practical experience obtained in evaluating different irrigation systems, should be useful as necessary but insufficient inputs to the site-specific evaluation required.

ACKNOWLEDGMENT

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Modeling Salinity of Irrigation Return Flow where Sources and Sinks are Present

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ABSTRACT

Managing irrigation return flow when salinity sources and sinks are present presents many complex difficulties. Models developed to include the source sink term in an empirical way show that wide variations in irrigation quality and quantity will have little influence on return flow for many years where the source-sink term is important. The quantity of salt in return flow is primarily determined by water flow because the soil solution concentration changes very slowly. Where a water table is present, successful irrigation might be practiced with no return flow for some conditions. Even where no source-sink term is considered, model predictions indicate irrigation management with no return flow for several years is possible with little reduction in yield. The influence of irrigation system uniformity is shown to be significant over several years time. Thus, it is evident that many possiblities for return flow management exist but the long term effects should not be overlooked.

INTRODUCTION

Prediction of the influence of irrigation management on irrigation return flow quality and salinity of the root zone must be possible if future irrigation is to be successful over a long period of time. Many presently successful irrigation systems based on design criteria that ignore the salinity of the irrigation return flow may need to be modified or changed to meet new restrictions on irrigation return flow quality.

Many models have been developed to predict the influence of irrigation management practices on the salinity of the soil and drainage water where the soil has been assumed to be inert (summarized by Childs and Hanks, 1975). However, many soils are not inert. Soil chemical reactions have strong source-sink properties such as exchange, precipitation, and solution. These processes are especially important in soil-water systems having a predominance of calcium and magnesium sulfates. Some authors have used chemical models to account for the source-sink processes and have obtained good predictions of soil solution and drainage water solution and drainage water salinity for some limited laboratory and field situations (Tanji et al., 1972; Dutt et al., 1972; and Oster and Rhoades, 1975). The water flow portions of these models have been quite restrictive so that many field situations cannot be simulated.

Consequently, we have been interested in the development of a predictive model that is comprehensive enough to include most field related processes of water and salinity variation related to irrigation return flow. The current model (Nimah and Hanks, 1973) involves a comprehensive water flow portion that accounts for irrigation, rainfall, drainage, evaporation, and transpiration (and thus root uptake). A salinity modification which accounts for mass and diffusion flow was made by Childs and Hanks (1975). This modification has also been used to predict the effect of salinity and irrigation management on crop production. The Childs-Hanks modification could not account for the strong source-sink tendencies of the soil studied at Vernal, Utah as discussed by Bliesner et al. (1977), so a further modification has been made as described by Melamed et al. (1977).

MODEL DESCRIPTION

The flow of water in the soil during irrigation must be predicted so soil profile salinity can be assessed. The basic water flow equation for one-dimensional flow is

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial Z}\right) + A(z,t) \qquad (1)$$

where θ is volumetric water content, t is time, z is depth, $K(\theta)$ is hydraulic conductivity, H is hydraulic potential and $A(z,t)$ is the root extraction term. The root extraction term is given by

$$A(z,t) = \frac{[HR + (1.05 \cdot z) - h(z,t) - \Delta(z,t)] \cdot RDF(z) \cdot K(\theta)}{\Delta x \cdot \Delta z} \qquad (2)$$

where HR is the effective root water potential at the soil surface ($z = 0$), the quantity "$1.05 \cdot z$" is a combined term to account for friction loss in the root and gravitational head loss within the root, h is the soil matric potential, Δ is the soil solution osmotic potential, RDG (z) is a root density function, Δx us the distance between the roots and the point in the soil where $h(z,t)$ and $s(z,t)$ apply and Δs is the depth increment. Nimah and Hanks (1973) have given details for the solution of the above two equations.

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta,q)\frac{\partial C}{\partial z} - \frac{\partial(qC)}{\partial z}\right. + \alpha K_s\,(R-C) \qquad (3)$$

where C is the concentration of the soil solution, q is the water flux, α is 1 or 0 depending on the presence of soluble salts or on the value of R and C, R is the soil solution concentration at equilibrium where no precipitation or dissolution takes place and K_s is a transfer coefficient. If $C > R$, precipitation will occure and if $C < R$ dissolution will occur provided there are soluble salts in the solid phase. $D(\theta,q)$ is the apparent diffusion coefficient (the sum of the molecular diffusion and the hydrodynamic dispersion). More details involving the solution of the above equation are given by Childs and Hanks (1975) and Melamed et al. (1977). Another consideration involved in the solution of equation (3) is the amount of solid phase salts in the profile that can be dissolved.

The last term of equation (3) accounts for the source-sink properties of the soil-water system. As given, it is empirical and has many limitiations not the least of which is how to define the variables as discussed by Melamed et al. (1977). The value of R and the source strength must be determined by a calibration type procedure from field data. The value of R, at present, is taken as the measured soil solution concentration provided there is a source of soluble salts present. The source strength is estimated from a comparison of the concentration of the soil solution and the concentration of a 1:5 or 1:10 dilution. As now defined, the model is primarily useful for leaching studies because once the solid phase salts are all dissolved the value of R is not defined. Further work is presently being done to quantify this source-sink term in more basic terms.

MODEL CAPABILITY

The model in its present form is quite general and has been used for a wide variety of predictions. Several varieties of input information are needed. Soil hydraulic properties must be known for prediction of water flow. Soil chemical properties are needed for salinity prediction. Initial soil water and salinity status at the beginning of the prediction period are also needed.

Plant properties are also needed as input conditions to the model. These include root depth and plant cover-time relations. The plant cover-time relations are required to estimate the portion of potential evapotranspiration that is potential transpiration.

Climate factors needed as input conditions are: potential evapotranspiration and rainfall as related to time during the season. Irrigation input data needed are: irrigation amount and salinity, and time of occurrence of the irrigations.

The model will produce a wide variety of output information, some of which may not be useful depending on the reason for the prediction. Soil water and salinity profiles, amount and salinity of drainage water are among the most useful data available from the model. Of particular interest is the prediction of relative transpiration because this has been shown to be related to dry matter yield by the following equation (Hanks, 1974):

$$\frac{Y}{Y_p} = \frac{T}{T_p} \qquad (4)$$

where Y is dry matter yield for transpiration, T, and Yp is potential dry matter yield where transpiration is not limited, Tp, by soil water. This yield prediction is very useful for many management decisions related to irrigation treatment, timing, etc.

MODEL PREDICTIONS

Many model predictions of irrigation management effects on salinity of the root zone have been made as outlined in detail by Childs and Hanks (1975) and Melamed et al. (1977). Where the source-sink term is not important and for the specific field conditions simulated, the predicted influence of amount of irrigation and initial salinity of the soil solution are shown in Table 1. The data indicate an increase in relative transpiration (thus relative yield) as irrigation amount increases and also as the initial soil salinity decreases. The data also show considerable upward flow from the water table (negative drainage) where irrigation was less than water use. Where water movement is upward from the water table the final salt concentration increased.

Figure 1 shows some predictions of relative yield as related to time in years for two different amounts of water added, both of which were less than evapotranspiration so that salt was building up with time. Where irrigation was highest, relative yield did not decrease for about 6 years whereas with low irrigation, relative yield decreased continuously. This demonstrates that even when no leaching occurs, yield might not be decreased for several years.

One other interesting simulation was done to evaluate the influence of different values of irrigation uniformity on relative yield where the average leaching was the same. Under any practical irrigation system, water is applied unevenly. While the average application rate may indicate no salt buildup because drainage occurs, there may be areas of the field receiving sufficiently less irrigation so that no drainage occurs and thus salt builds up over time. The results of the predictions, shown in Table 2, simulate a good sprinkler system (Cu = 0.88) and a poor gravity system (Cu = 0.42). The data show that yield varies because of non-uniform water application and that the high uniformity system causes higher average yields than the low uniformity system. After five years, there was a larger decrease in yields for the low uniformity. The result is caused by higher salt buildup, on the average, for the lower uniformity system. In addition, more salt outflow into the drains occurred for the low uniformity than for the high uniformity. Many other simulations were made for an inert soil (Childs and Hanks, 1975).

However, when comparing the simulation with the field measurements, it became apparent that the soil was not acting like an inert medium. When this result became apparent, a field trial was set up with different leaching fractions, different depths to the water table, and different qualities of irrigation water as described by Bliesner et al. (1977). Figure 2 shows these field results where regardless of the depth to the water table, there was no appreciable change in soil solution EC. If the soil were inert the change in EC would have been appreciable as shown. Similar results were shown by Bliesner (1977) for different leaching fractions and quality of the irrigation water. This is evidence that there was a strong source-sink potential for this soil. Thus efforts were made, as discussed earlier, to incorporate the source-sink effect in the model. The details of this effort have been reported in detail by Melamed et al. (1977) and Hanks et al. (1976). Figure 3 shows a laboratory leaching trial, using the soil from Vernal, with and without the source-sink term included. This comparison between measured and computed EC is good provided the source-sink term is accounted for. Figure 4 is the result of a laboratory leach trial similar to that shown in Figure 3 except that it was terminated much sooner. The EC of the soil solution and the quantity of solid salts were measured throughout the profile. The agreement between measured and computed data is good. The solid salts were estimated by taking the EC of the soil solution extract and comparing it with the EC of a 1:5 extraction. The 1:5 extraction was assumed to be a measure of the total salinity for the purposes of these studies. More dilute extraction would be needed if the amount of solid phase salts is very large.

The real test of a model must be made for actual field conditions. This was done and results are illustrated in Figures 5 and 6. The field data came from plots with large quantities of water. When the source-sink term was not considered in the model, the simulation was very poor. When a uniform source sink term, R = 5 mmhos/cm, was used the simulation was also poor. Good simulation was obtained only when the R value was taken as a variable with depth. The R value was assumed to be the initial concentration of the soil solution measured before irrigation was applied. The simulation, with a variable R, was not as good at 26 hours, shortly after an irrigation with 25 cm of water, as at 49.5 hours. This was probably caused by the value of the transfer coefficient, K, which was too low.

A simulation using the chemical equilibrium model of Dutt (1972) was also made. This model not only did not give good results, but also gave an almost uniform salinity profile. This is probably a result of using a uniform ratio of cations and anions in the computation. This was done because only limited data were available. It was assumed that there was gypsum throughout and that the ratios of Mg^{++} / Ca^{++} and Na^{++}/Ca^{++} were 0.40 and 0.14, respectively, and the ratios of Cl^- /$SO_4^{=}$ and HCO_3^- /$So_4^{=}$ were 0.24 and 0.01, respectively. It may be that a modification of different chemical species that change with depth could be found that would give a better explanation. However, it is difficult to envision changes that could account for a profile that was not uniform with depth and did not change appreciably when irrigated with the large amount of water used in this study.

It should be emphasized that the source-sink part of the model reported herein is limited to fields like those encountered. Having to use a variable R (measured from field data) causes the model to be useful only for leaching studies. Once the excess solid salt in the profile is leached, there is no reason to expect that the same value of R would again apply at the same depth for a situation where precipitation would occur with different salt species. To be able to predict the changing value of R will probably involve complex chemical models. Thus, we conclude the model is useful to predict changes involving dissolution but will not be too useful for predicting salt precipitation until some logical method for predicting the value of R is found.

With these limitations in mind we have made model predictions simulating different leaching situations using the field data from the Ashley Valley (Vernal), Utah farm. The soils and climatic data are the same as used by Childs and Hanks (1975) except for the initial salt concentration profiles. The crop studied was alfalfa with a rooting depth pattern that did not change with time. A typical growing season was taken as 125 days and was assumed the same for all years. Irrigation was applied at about 15-day intervals at approximately equal amounts. Potential ET was 81.5 cm of which E_p (evaporation) = 8.8 and T_p (transpiration) was 72.7 cm.

Figures 7 and 8 show the profiles of salt concentrations in both the solution and solid salt concentrations in the profile for a series of model simulation runs totaling 7 years. The total irrigation applied was 106 cm (30 percent leaching) each year with a concentration of 2 meq/l in the irrigation water. With this situation 25 cm of water leached out of the profile each year. There was a water table at 160 cm. The value of R was considered variable with depth and was taken to be the same as the initial solution concentration shown in Figure 7. The amount of solid salt present at the beginning of the first year was estimated from the difference between the electrical conductivity of the saturation extract and 1.5 extract as given by Melamed et al. (1977).

The predictions of this model show (Figure 9) that it took 7 years to leach the stored salts out of the soil profile. The amount of salt going into the drainage water was simply the product of the relatively constant concentration of the soil solution just above the water table and of the total water drained out. The model predicted precipitation of salts near the bottom of the profile and solid salt dissolution in the upper part of the profile. There was a net equal removal of salt from the profile every year.

These data indicate that a long time period is needed to cause any significant changes in the soil profile salt situation. The predictions agree with the measurements of Bliesner et al. (1977) that considerable variation in leaching fractions and irrigation water quality over a single growing season had very little effect on the soil solution concentration. This was borne out by preliminary computations made with a leaching fraction of near zero which predicted essentially no change in solution concentration over several years.

Figures 9 and 10 show soil solution and solid salt concentrations for a condition of ET equal to 81.5 cm and with 106 cm of total irrigation having a concentration if 10 meq/l in the irrigation water. In this situation the salts added are just slightly more than those removed. After 3 years a stable soil solution concentration was predicted. However, there was a redistribution of solid salts from the surface toward the bottom of the profile.

IRRIGATION MANAGEMENT

The model results indicate that where the source-sink phenomenon is important that there are many management implications. The first implication is that, over a period of time such as a year or two, the soil solution and drainage water concentrations will change very little regardless of the irrigation management imposed. Consequently the salt load of the drainage water can be evaluated by measuring the water flow to drainage and multiplying it by the salt concentration of the drainage water. Since the solution concentration of the drainage water changes so slowly, yearly measurements of the solution concentration should be sufficient for purposes of monitoring. Thus, the most critical measurement is the total water flow to drainage. This also implies that any experiment designed to measure influences of irrigation management variables on drainage water quality in these systems must be conducted over many years.

A second important implication is that irrigation management could be practiced with no leaching at all. Model predictions indicate this could go on for a long period with no adverse effects, provided soil water storage depletion plus irrigation and upward flow are flow are equal to evapotranspiration.

Caution should be used in accepting this conclusion. If salts were precipitated, there would be a limit beyond which there would be no void space left in the soil for solid salt storage. This limit would not be reached for a long period of time, however. An examination of the irrigation management practices over the years in Ashley Valley, Utah, have indicated that this situation has actually occurred for many years. Irrigation is with gravity systems which apply water with a very low degree of uniformity. Farmer practice has been to irrigate a few times a year with high amounts of water. Good yields have resulted. There is a water table near the surface (EC of about 2 mmhos/cm) which supplies water between the infrequent irrigations. The soils in the area are heterogeneously permeable which would contribute to a highly variable amount of water moving through the soil on a field. Yet the yields are not variable over the fields. Water moving up from the water table has apparently supplied crop needs in th under-irrigated areas without causing yield decreases over the years. Most of the salts transported by the water moving up have apparently precipitated out of the soil solution. This process has been going on for about 50 years with no problems with crop production — in fact a very simple and efficient irrigation management system has developed.

To illustrate further the above situation, the results of a field experiment on alfalfa conducted in Ashley Valley in 1975 are cited. Salinity level and irrigation amount variables were established on mature alfalfa. Six levels of initial salinity were imposed by adding water with different levels of salt concentration (using calcium chloride) at the beginning of the season with the highest level being 6 mmhos/cm. Water applied was varied from 0 to more than evapotranspiration. There was no influence on alfalfa yields due to either salinity or water application treatment. Water coming from the water table apparently supplied the needs of the plants where no irrigation was applied. There was a difference in soil profile salinity due to treatment near the surface but not below 45 cm.

CONCLUSIONS

Use of a model that contains a relatively simple source-sink modification has provided an in sight into the behavior of an irrigated soil that did not respond to water management variables. Refinement of the model will allow prediction of a water management technique that includes both precipitation and dissolution of the salt in the profile. On a short-term basis, control of the amount of return flow is the only way to reduce salt contributions from irrigated agriculture.

TABLE 1

Comparison of irrigation water applied and initial salt concentration on relative transpiration of the medium deep root crop T/T_p, total water used, drainage, salt concentration. Irrigation quality is 6.35 meq/liter. Note that (-) drainage indicated net upward flow from the water table

Irrigation and rain	*T*	*T/T_p*	*Drain age*	*Salt flow to ground water*	*Initial salt concentration*	*Final Salt concentration average*
cm			cm	kg/ha	—meq/liter—	
5.6	25.0	0.51	-9.4	—	20	44
5.6	24.0	0.49	-9.1	—	50	102
5.6	15.8	0.33	-7.5	—	200	278
10.3	28.2	0.59	-9.1	—	20	42
10.3	27.2	0.57	-9.0	—	50	94
10.3	19.1	0.40	-7.4	—	200	269
15.0	32.4	0.68	-8.9	—	20	42
15.0	31.4	0.65	-8.8	—	50	93
15.0	23.1	0.49	-7.3	—	200	268
24.4	40.5	0.87	-8.5	—	20	42
24.4	39.6	0.86	-8.3	—	50	91
24.4	32.3	0.70	-6.9	—	200	263
43.2	46.3	1.00	-5.2	—	20	27
43.2	46.3	1.00	-4.9	—	50	62
43.2	44.6	0.96	-4.1	—	200	225
56.4	47.9	1.00	0.56	90	20	24
56.4	47.9	1.00	0.56	247	50	52
56.4	47.9	1.00	0.43	740	200	195
63.5	47.9	1.00	9.30	1614	20	21
63.5	47.9	1.00	9.40	4036	50	44

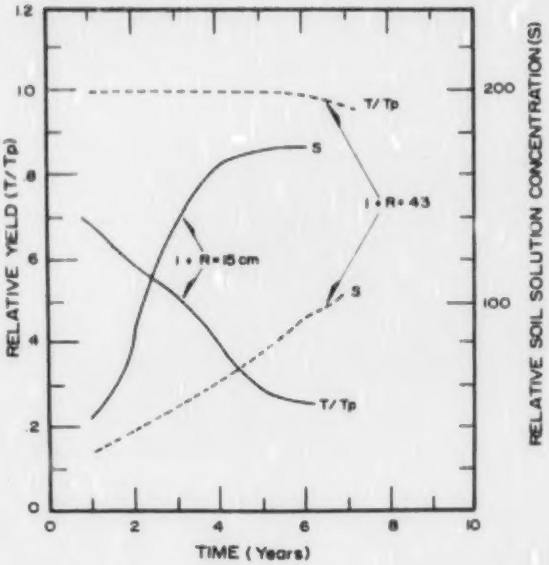

Figure 1. Computed relative yield (T/T_p) and relative soil solution concentration for two different irrigation amounts as related to time. I is irrigation and R is rainfall (After Childs and Hanks, 1975).

TABLE 2

Example of uniformity calculations — 5-year sequence for shallow rooted crop

Irrigation and rain	*Area**	*Year 1*			*Year 5*		
		Rel. yield	*Salt outflow*	*Final soil salinity*	*Rel. yield*	*Salt outflow*	*Final soil salinity*
cm	%		kg/ha	meq/liter		tons/acre	meq/liter
				Cu = 0.88 Parabolic Distribution			
40.4	10.4	0.85	—	27.6	0.84	—	70.8
46.7	24.8	0.92	—	25.7	0.91	—	52.5
53.1	29.6	0.96	—	23.9	0.96	—	38.7
59.5	24.8	0.99	516	22.4	0.99	0.03	29.6
65.8	10.4	1.00	1233	21.2	0.99	0.64	24.0
Average		0.95	247		0.95	0.14	
				Cu = 0.42 Rectangular Distribution			
10.6	20.0	0.50	—	32.3	0.39	—	161.6
31.9	20.0	0.75	—	29.9	0.68	—	50.5
53.1	20.0	0.96	—	23.9	0.96	—	38.7
74.3	20.0	0.96	2556	20.4	0.96	1.19	21.1
95.6	20.0	1.00	8138	20.0	1.00	3.86	20.0
Average		0.83	2175		0.80	1.02	

*The percent of the area having the average irrigation and rain in the left.

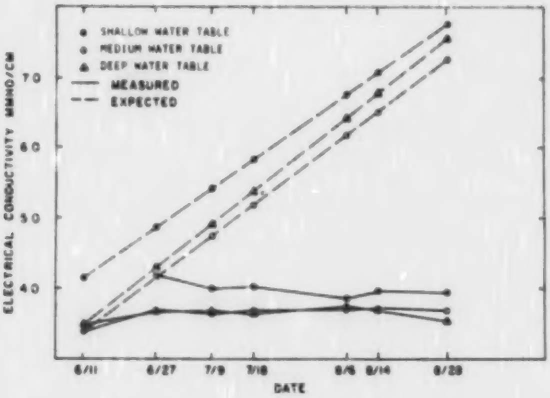

Figure 2. Measured and expected (assuming an inert soil) average soil water salinity with time for three depths of water table (After Bliesner et al., 1977).

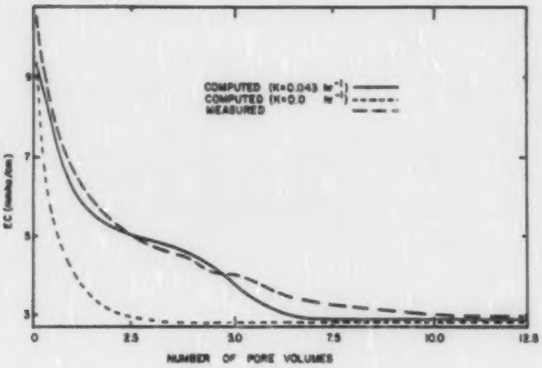

Figure 3. Computed and measured electrical conductivity of the effluent during a laboratory leaching trial for Mesa sandy clay from Vernal, Utah (after Melamed et al., 1977).

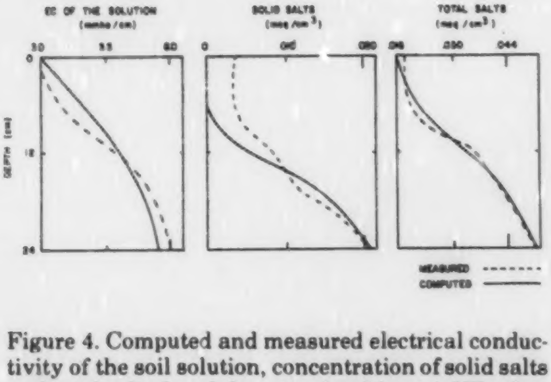

Figure 4. Computed and measured electrical conductivity of the soil solution, concentration of solid salts and total salts for a laboratory leaching trial like that of Figure 3 (after Melamed et al., 1977).

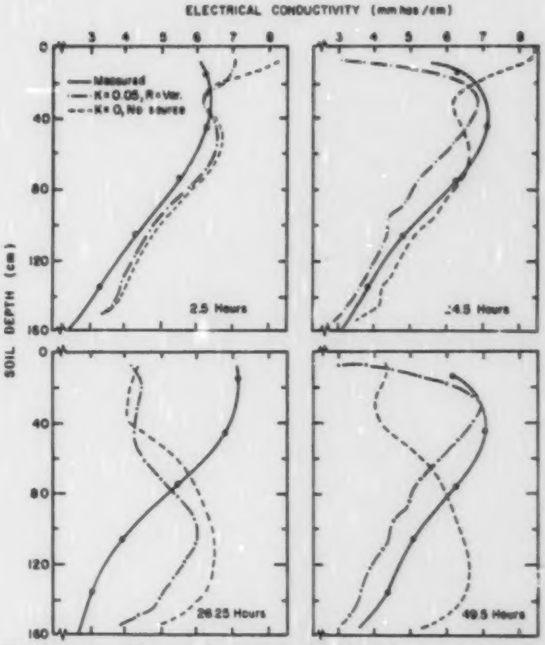

Figure 5. Measured and simulated comparisons using no source-sink term (K = 0.0) with a variable source-sink term (R = Var) for the Vernal, Utah field trial (after Melamed et al., 1977).

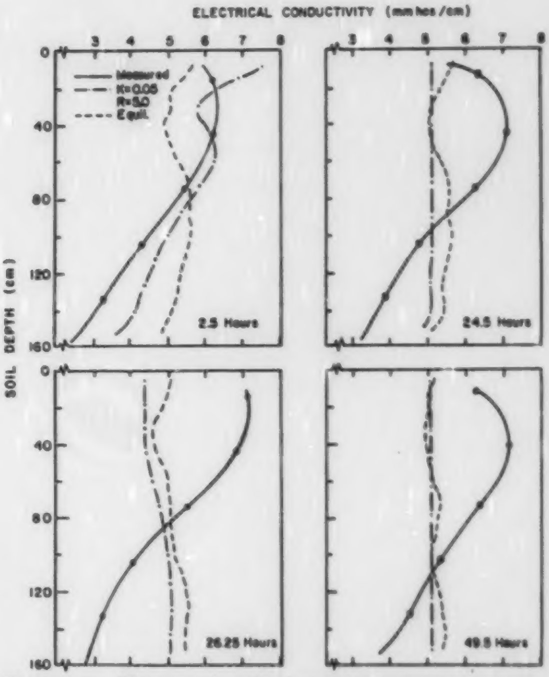

Figure 6. Measured and simulated comparison using a constant source-sink term (R = 5.0 mmhos/cm) and a chemical equilibrium model for Vernal field trial (after Melamed et al., 1977).

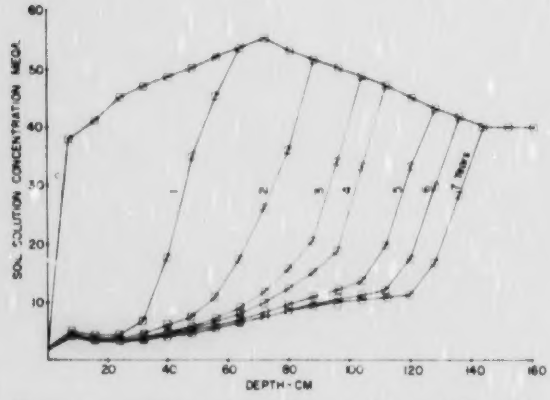

Figure 7. Soil solution concentration profiles computed for 7 years for a total irrigation of 106 cm/year, with good water quality (2 meq/l) and evapotranspiration of 81.5 cm.

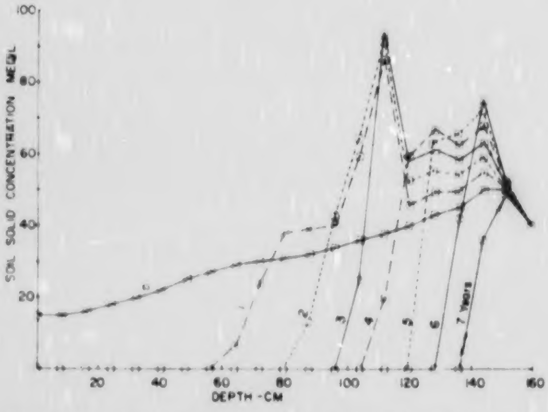

Figure 8. Soil solid salt concentration profiles computed for 7 years for the same conditions as Figure 7.

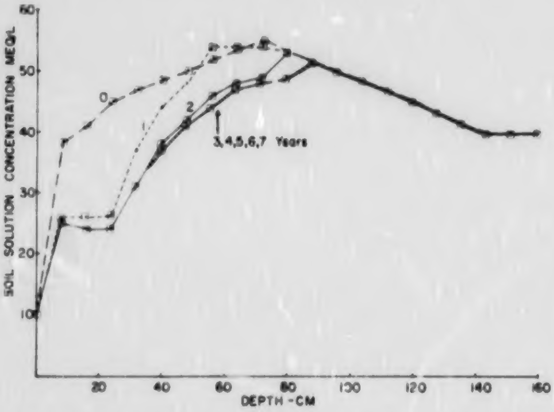

Figure 9. Soil solution concentration profiles computed for 7 years for a total irrigation of 106 cm/year with poor quality water (10 meq/l) and evapotranspiration of 81.5 cm.

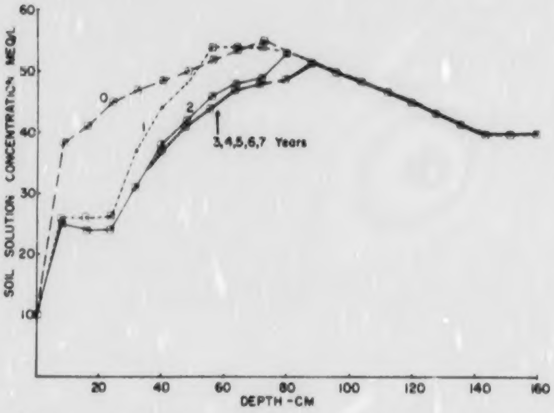

Figure 10. Soil solid salt concentration profiles computed for 7 years for the same conditions as Figure 9.

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Field Evaluation of Sprinkler Irrigation for Management of Irrigation Return Flow

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ABSTRACT

Sprinkler irrigation offers one alternative for control of irrigation water application that influences quality of return flow. A two-year field scale study of soil solution response to controlled water application using sprinklers was conducted in the Ashley Valley near Vernal, Utah. The design level of water control was attained with high coefficients of uniformity but the soil solution did not respond as expected. The soil acted both as a source and a sink for salt. Root zone salinity was only slightly affected by different leaching fractions. Minimum average leaching fractions obtainable are influenced by both the hydraulic design and operation of the system.

INTRODUCTION

Mechanical control of irrigation by sprinkle or drip systems allows application of more precise amounts of water than do surface irrigation methods. With mechanical irrigation it is possible to apply water continuously, intermittently, or in any prescribed amount. The only restraint on a mechanical irrigation system is the water absorption rate. As long as the application rate is lower than the infiltration rate of the soil, water can be applied at any rate and in any amount. With surface water application methods, the amount applied and the application rate is ultimately controlled by the soil.

Since sprinkle irrigation allows management control of the amount of water applied, this irrigation method may offer a means of controlling the amount of return flow. Reduction in the amount of return flow is usually accomplished by reducing the leaching fraction or reducing the amount of water applied relative to potential evapotranspiration. Studies have indicated that reducing the leaching fraction will decrease the total salt loading from irrigation return flow. Rhoades (1) has suggested that minimizing the amount of drainage water maximizes precipitation of calcium carbonate and gypsum in the soil, minimizes soil weathering, minimizes the dissolution of salts previously deposited in the soil and thereby maximizes the amount of soluble salts retained in storage in the soil profile.

Bernstein and Francois (2) of the U.S. Salinity Laboratory found that leaching fractions could be reduced to as little as one-fourth the values recommended by the U. S. Salinity Laboratory without reducing yields on alfalfa. Their research indicated that the lower portion of the root zone may become highly salinized as long as sufficient good quality water is applied in the upper root zone.

Leaching fractions as low as two to three per cent have been recommended in recent years. Leaching fractions of this low magnitude are actually being attained due to soil conditions in the Imperial Valley. Measurements of electrical conductivity drain effluent discharge indicate that these low leaching fractions are common. In the Imperial Valley, however, the infiltration characteristics of the soil and the low internal permeability rather than method of

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irrigation controls the leaching fraction. In other soils which are more permeable, mechanical means of water application control will be required if low leaching fractions are to be attained.

FIELD STUDY PROCEDURE

The U. S. Environmental Protection Agency supported a study by the Agricultural and Irrigation Engineering Department and the Soils and Biometeorology Department of Utah State University to determine the capability of a commercially available irrigation system to attain the level of control necessary to achieve the low leaching fractions suggested in the literature. The system chosen for evaluation was a portable solid-set sprinkler system using No. 30 WSTNT Rain Bird Sprinklers with 0.36 mm (9/64 in.) nozzles on a 9 m by 15 m (30 ft. x 50 ft.) spacing. The operating pressure was approximately 4.1 atm (60 psi). The system was used to irrigate 8.1 ha (20 acres) of alfalfa and designed so that four adjacent lines were operated simultaneously.

For the purpose of evaluation, a precipitation catch system using cans on a 1.5 m (5 ft) grid spacing was set up in the approximate center of the field using the two inner lines of a four line set. Plants in the area of the catch were clipped prior to each irrigation to keep the alfalfa below the tops of the catch cans. The depths of catch, wind movement, line pressure, sprinkler discharge, and pan evaporation were measured for each irrigation throughout the season. Water was collected for the full duration of each irrigation.

The distribution uniformity of each irrigation was estimated by using Christiansen's Coefficient of Uniformity. In addition, several other water distribution calculations were made including potential irrigation efficiency, low quarter distribution uniformity, and low catch distribution uniformity.

The average operating pressure for all tests was 4.1 atm (60 psi). The average wind velocity for each catch ranged from 2.04 km/hr (1.27 mph) to 8.77 km/hr. (5.45 mph) with an overall average of 4.07 km/hr (2.53 mph). The wind direction for each irrigation was west-southwest. Wind speed in the range shown did not seem to have a significant effect on uniformity of water application. Full details of the study are reported by Bliesner (3) and Bliesner, et al (4).

RESULTS

Results of the can-catch data for seven individual irrigations are shown in Table 1. The table shows the depth applied, the average depth caught, the average caught in the low quarter of the area, the absolute low catch and the Christiansen Coefficient of Uniformity.

TABLE 1

Sprinkler uniformity measurements for individual irrigations.

Date	*Depth Applied*	*Ave. Depth Caught*	*Ave. Depth Low 1/4*	*Low Catch*	*CU*
	in*	in*	in*	in*	
6/05/74	5.17	4.70	3.80	3.57	86.
6/23/74	3.19	3.07	2.53	2.39	88.
7/04/74	3.18	2.84	2.49	2.33	92.
7/17/74	3.28	3.64	2.92	2.58	87.
8/02/74	4.10	3.93	3.53	3.38	94.
8/14/74	3.19	2.99	2.53	2.43	91.
8/24/74	4.93	4.75	4.01	3.65	89.

*multiply by 25.4 to get depth in mm.

Coefficients of Uniformity varied from a low of 86 to a high of 93. The Coefficients of Uniformity indicate that it is possible to get good uniformity of water application with a commercial sprinkler system.

The uniformity is further improved if the water application is composited over the season. Table 2 shows the same data for the individual irrigations but combines the effects of individual uniformity measurements progressively over the season. Variations that occur in a single irrigation are sometimes compensated by subsequent irrigations. Table 2 shows a continued increase in the Coefficient of Uniformity over the season. The Coefficient of Uniformity increased from 86 per cent for the first irrigation to 94 per cent for the composite of all seven irrigations.

To determine whether an additional management practice would improve uniformity of distribution, a calculated composite uniformity for the system was developed, assuming that every other irrigation was an alternate set. That is, the sprinklers were moved laterally one-half spacing every other irrigation. Using the data collected during the season and compositing the alternate sets over the season, the Coefficient of Uniformity for the seven irrigations was raised to 98 per cent as shown in Table 3.

In irrigation management to control leaching, the most important aspect of the system is distribution uniformity. In order to avoid salt build-up, the minimum desired leaching fraction should be attained at every point in the field. Unless the irrigation system is capable of 100 per cent uniformity of application, all but the least watered area will receive more than the desired minimum leaching when the minimum leaching requirement is applied to the least watered area.

TABLE 2

Cumulative composite sprinkler uniformities for the season.

Date	*Depth Applied*	*Ave. Depth Caught*	*Ave. Depth Low 1/4*	*Low Catch*	*CU*
6/05/74	5.17	4.70	3.80	3.57	86.
6/23/74	8.36	7.77	6.48	6.19	87.
7/04/74	11.54	10.61	9.21	8.80	90.
7/17/74	15.30	14.25	12.50	11.93	91.
8/02/74	19.55	18.18	16.51	15.79	94.
8/14/74	22.74	21.17	19.22	18.39	93.
8/24/74	27.67	25.92	23.51	22.60	94.

TABLE 3

Computed alternate set composite sprinkler uniformities for the season.

Date	*Depth Applied*	*Ave. Depth Caught*	*Ave. Depth Low 1/4*	*Low Catch*	*CU*
6/05/74	5.17	4.70	3.80	3.57	86.
6/23/74	8.36	7.77	7.11	6.90	95.
7/04/74	11.54	10.61	10.11	9.87	97.
7/17/74	15.39	14.25	13.24	12.83	95.
8/02/74	19.55	18.18	17.18	16.90	97.
8/24/74	22.74	21.17	20.07	19.73	97.
8/24/74	27.57	25.92	24.95	23.95	98.

Although Coefficient of Uniformity is a qualitative measure of water distribution, it is helpful to see the percentages of the field involved in over- and under-irrigation. Figures 1 and 2 show the full season composite can-catch water distribution expressed as a percent of area receiving a given percentage of the average application depth or more. Figure 2 shows the effect of compositing alternate can-catch data to improve the distribution. Figure 1 shows that the minimum application was approximately 86 per cent of the average and the maximum application was 118 per cent of the average. Compositing and using the alternate set procedure resulted in a decrease of the minimum catch to 91 per cent and the maximum catch to 109 per cent of the average. Further examination of Figure 2 illustrates the problem of using very low leaching fractions when actual distribution uniformity is considered. For example: 20 per cent of the field received 97 per cent of the average application or less. This means that 20 per cent of the field would be accummulating salt since 20 per cent of the field received 97 per cent or less than the average application. Or, in other words, only the portions of the field receiving 97 per cent of the average application or more would receive any leaching at all. The remainder of the field would be accumulating salt. Figure 2 shows the seasonal composite alternate set can-catch and indicates that 12 per cent of the field would be accumulating salt with a 3 per cent leaching fraction.

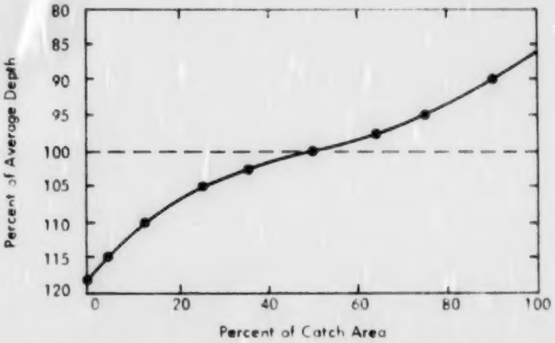

Figure 1. Seasonal composite can catch water distribution expressed as the percent of area receiving a given percent of average depth or more.

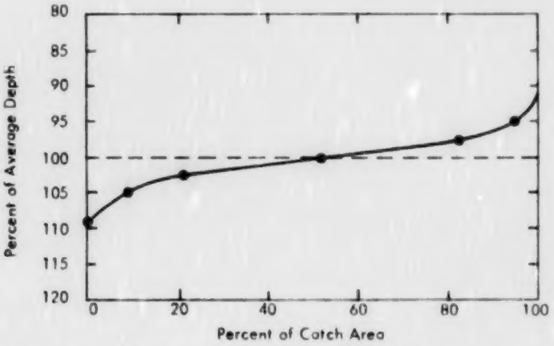

Figure 2. Seasonal composite alternate set can catch water distribution expressed as the percent of area receiving a given percent of average depth or more.

The above data refers only to the uniformity of water distribution within four sprinklers at a given location in the field. Another factor effecting the water distribution of the sprinkler system is the normal pressure variation designed into the system. Under strict management or automation, it is possible to operate a system so that the supply ends of all the laterals are at the same pressure. If the standard 20 per cent friction loss in a lateral is allowed, then the pressure at the first outlet is 1.25 times the pressure at the last outlet. The discharge at the head of the line, therefore, is 12 per cent higher than the discharge at the end of the line, and the average discharge is 2-1/2 per cent higher than the end discharge. Combining this pressure variation along the lateral with the results from the can-catch analysis yields a minimum attainable average leaching fraction for the total field of 15 per cent for the seasonal composite and 10 per cent for the alternate set composite pattern assuming that the least watered area receives zero leaching. The maximum leaching fraction anywhere in the field would be 34 per cent for the seasonal composite and 24 per cent for the alternate set composite. Again, the absolute minimum leaching fraction would be zero.

Since the uniformity values of this field system are high compared to most field sprinkler systems, the minimum average leaching fraction that could realistically be expected from a solid set sprinkler system would be 10 percent. To obtain average leaching fractions lower than this minimum value will cause areas of salt build-up in the field since part of the area actually has a zero leaching fraction. The resulting salt build-up could be detrimental to crop production.

As part of the same experimental effort, a study was made of the effect of leaching fraction on soil salinity profiles using the sprinkler system to apply water. The experiment was designed to test the interaction of three leaching fractions and the salinity of the applied water. Leaching fractions were designed to be zero and were otherwise varied to give a theoretical drain discharge conductivity of 25 mmhos/cm and 8 mmhos/cm. The leaching fractions were referred to as low, medium and high. The average leaching fractions were approximately 0, 10 and 25 per cent. Figures 3, 4, and 5 show profile salt contents on three dates during one of the irrigation seasons for low, medium, and high leaching fractions, respectively. The salt

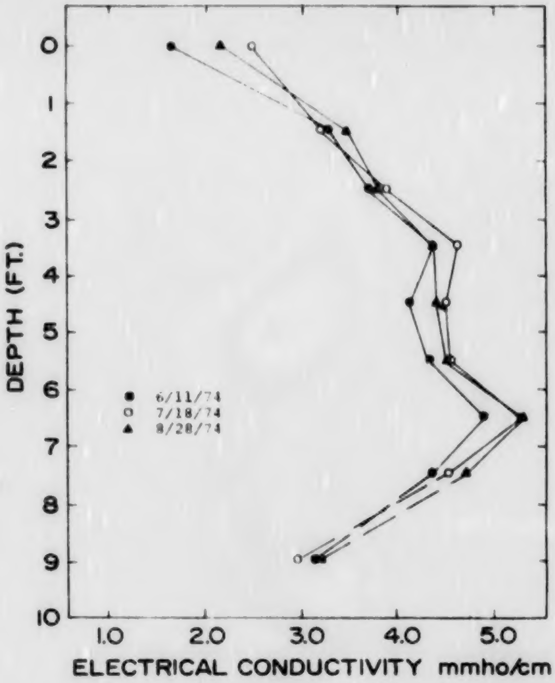

Figure 3. Average soil solution salinity profile for low leaching plots on three dates.

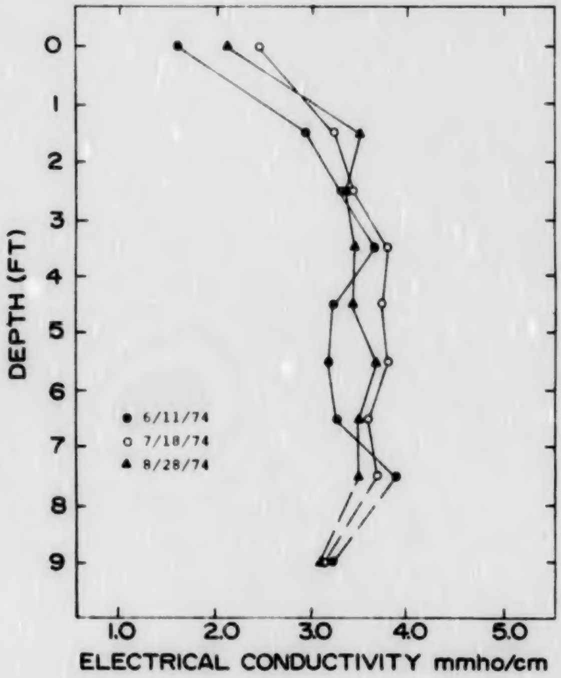

Figure 4. Average soil solution salinity profile for medium leaching plots on three dates.

content of the soil profile did not change significantly under any of the treatments imposed during the irrigation season. The same result was observed during the second year that the study was conducted. Figure 6 shows the measured and expected average soil salinity changes with time for the three leaching treatments. The expected values of average soil water salinity rose to values above 7 mmhos/cm, but the average measured values remained at approximately 4 mmhos/cm. This particular soil acts as either a source or a sink for salt depending on water management. Figures 3, 4, and 5 indicate that short term management of leaching fractions will not significantly effect the salinity at the bottom of the root zone. Management of the return flow becomes a matter of managing the quantity of return flow on a short term basis, since the quality of return flow shows little change due to management.

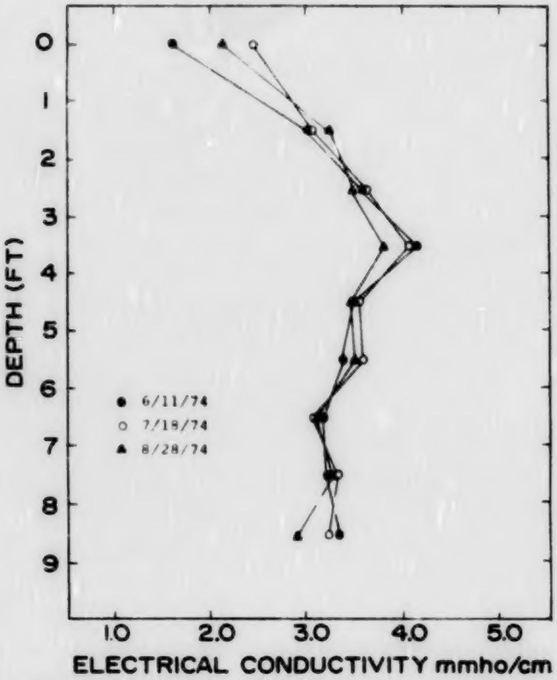

Figure 5. Average soil solution salinity profile for high leaching plots on three dates.

CONCLUSIONS

Sprinkle irrigation offers one alternative for irrigation water application control that will influence the quantity of return flow. The field studies conducted emphasized the importance of obtaining uniform water application in order to prevent salt build-up in parts of the field. Compositing the water application over a full season improves water distribution but there are still areas within individual sprinkler patterns that receive inadequate amounts of water to accomplish minimum leaching. Variations along sprinkler laterals will further complicate the nonuniformity problem. In the field, the leaching fraction varied from 0 to 34 per cent with an average of 15 per cent assuming that the least watered area was irrigated to exactly meet evapotranspiration. The alternate set composite showed a minimum application amount of 92 per cent of the average application. The average leaching fraction for composite alternate sets varied from 0 to 24 per cent with an average of 10 per cent. Uniformity of application and control of the amount applied is the key to successful management of irrigation return flow by sprinklers.

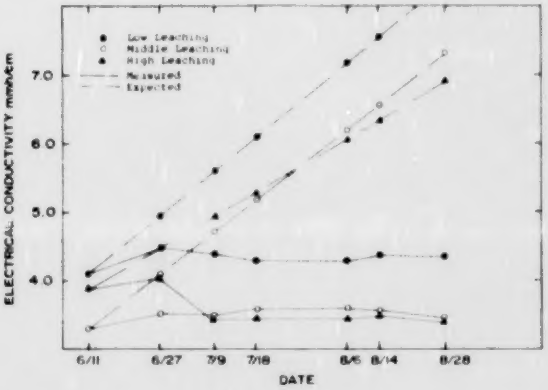

Figure 6. Measured and expected average soil water salinity changes with time for three leaching treatments.

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Effects of Irrigation Management on Soil Salinity and Return Flow Quality

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ABSTRACT

A field plot study was conducted to determine the effects of controlled surface irrigation and trickle irrigation on soil salinity, and on the quality and quantity of irrigation return flow. Changes in soil salinity were determined by taking extensive soil samples at least once a year. Return flow quality was measured on soil solution removed through vacuum samplers in the subsoil of each plot, and by analyzing the water quality at various levels below the groundwater and in a nearby drain. The quantity of return flow was estimated from crop growth and weather data, and amounts of water applied. This method was found more reliable than several other methods used for determining percolation losses.

Results of the first three years of this ongoing study showed that a larger change in soil salinity was produced by altering irrigation frequency than by changing irrigation efficiency. Irrigating when 50 percent of the soil-water had been depleted was the irrigation frequency most conducive to salt retention in the upper soil profile. However, different irrigation efficiencies and frequencies had no significant effect on cotton yield due in part to the large spatial variability of the physical properties of the soil at the site. The use of trickle irrigation was an effective method for controlling the volume of return flow, while maintaining relatively low salinity levels in the soil around the trickle lines. Accumulated salts were readily moved from the trickle lines by preplant irrigations and by intense rains. The mean salt concentration of the irrigation return flow, as estimated on soil solution samples removed by vacuum extraction from below the root zone, agreed well with the average salt concentration of the upper groundwater, but not with the quality of he deeper groundwater. The quality of the drain water was similar to the average composition of groundwater. The results of this study indicate that more efficient irrigation can reduce the volume of return flow, without immediate detrimental effects on crop yields or soil salinity.

INTRODUCTION

Maintaining the quality of river water is a major problem in the Western United States. In New Mexico, the salt concentration in the Rio Grande increases progressively going downstream from Santa Fe, in the north, to El Paso on the New Mexico-Texas border in the south. The greatest increases in salt concentration occur in reaches where irrigated agriculture is practiced. The increase per mile in concentration of dissolved solids was found to be more than twice as great in an irrigated area along the Rio Grande as in the non-irrigated area immediately to the north (Wierenga and Patterson, 1972). This greater increase in salt concentration in irrigated reaches is related to irrigation return flow. Irrigation return flow originates when water in excess of evapotranspiration is applied to the soil-plant system. The excess water is often applied intentionally to leach soluble salts from the plant root zone and insure perennial agriculture. That portion of the excess water flowing back to the river is called irrigation return flow.

The management of irrigation to minimize the effects of irrigation return flow water on downstream river water has received considerable attention in the past few years. For example, Rhoades et al. (1973, 1974) demonstrated that the salt burdens of percolated irrigation drainage waters could be appreciably reduced by minimizing the leaching fraction. Reduced drainage volumes effectively increased the precipitation of salts, reduced weathering of soil minerals, and reduced the total salt in the drainage waters. Suarez and Rhoades (1977) studied the effects of irrigation leaching management on river water quality. They concluded that the reduced salt load in the return flow may or may not reduce the salt load of river water, depending on the successive mixing and readjustment ot lower CO_2 levels of the return flow and the type or irrigation water. However, reduced leaching will result in reduced volumes or return flow. This latter conclusion was also reached by King and Hanks (1975), who found that total seasonal salt discharge from a tile drainage system was directly related to the quantity of water discharged. Reducing the volumes of return flow can be accomplished by improved irrigation management, including uniform application of water by controlled flooding, furrow, sprinkler, or trickle irrigation. Applying the optimum amounts of irrigation water for given climatic and soil conditions using irrigation scheduling programs such as the one developed by Jensen (1972), will also reduce the volume of return flow. The objectives of this paper are to present data on the effects of irrigation treatments on soil salinity in field plots irrigated with 1.2 mmhos / cm water over a three-year period.

METHODS AND MATERIALS

The experimental work was conducted on the Plant Science Research Center of New Mexico State University, about eight miles south and west of Las Cruces, New Mexico.

The soil at the site was heterogeneous which was characteristic of the alluvial soils along the Rio Grande Valley. The soils at the site were classified "typic torrifluvents" and "vertic torrifluvents". The soil profile consisted in general of about 30 cm silty clay loam over 20 to 30 cm of clay, over a variable amount of silty loam. The latter changed rather abruptly into a medium sand. However, the fine textured material in some plots was deeper, so that the depth to the sand on the two-acre site varied from 60 to 120 cm below the soil surface. Root penetration into the medium to fine sandy subsoil appeared to be almost negligible.

The experimental design consisted of thirty 7.3 x 7.3 meter plots. The plots were separated from the surrounding soil with polyethylene plastic to a depth of 75 cm below the soil surface. Wooden boards extending 20 cm above the soil surface and 10 cm below, covered with polyethylene plastic prevented surface runoff from the plots. Irrigation was by surface flooding the area within plot boundaries. All water was metered through a single flow meter installed in the main line. Prior to construction of the field plots, the area was leveled and flood irrigated with approximately 20 cm water. Further details on the experimental setup can be found in Wierenga (1977).

The treatments on the surface irrigated plots consisted of combinations of three frequencies of irrigation, with three field water application efficiencies, resulting in a total of 9 treatments. Each treatment was block randomized with three replications per treatment. The application efficiencies were 50, 75 and 100 percent for the first year of study, and 80, 90 and 100 percent efficiency for the last two years of the study. Frequency of irrigation was based on the amount of "available" water in the soil, with irrigations scheduled when 25, 50 or 75 percent of the available water was depleted from the root zone of the crop. Consumptive use at the experimental site was obtained during the first year of study from Class A pan evaporation data, corrected with a stage of growth dependent crop coefficient. During the second and third year of study, consumptive use was estimated from climatic data, using the Irrigation Management Scheduling Program (IMS), developed by Jensen (1972).

All plots were planted with cotton (Acala 1517-70) on a 1 m row spacing. Fertilizer was applied uniformly at a rate of 134 kg N / ha and 76 kg P_2O_5 / ha.

Efforts were made to determine the amounts of return flow, e.g. deep percolation water, from knowledge of the hydraulic conductivity and the hydraulic gradient as measured in each plot. Triplicate tensiometers were installed at two levels in each plot, well below the root zone in the sandy subsoil. The actual depths varied between 120 and 180 cm, below the surface, with a vertical distance of 30 cm between the two sets of tensiometers. Soil water tensions were determined with mercury manometers located outside each plot. Hydraulic conductivity as a function of water content was determined for three plots following the procedure described by Nielsen et al. (1964).

This procedure consists of thoroughly wetting the soil profile, covering the soil with polyethylene plastic, and measuring the hydraulic gradients and water contents during the drainage stage following infiltration. From the changes in water content of the soil profile with time and the gradients, the hydraulic conductivity could be calculated at various water contents.

Water contents within each plot were determined with a neutron meter. A calibration curve was established from neutron meter readings and gravimetric sampling of the soil within the plot area.

The quality of return flow was monitored with soil solution samplers installed at depths halfway between the two levels of tensiometers in each plot. The samplers were made with standard tensiometer cups, 5.8 cm long, attached to 2.2 cm O.D. PVC tubing. Vacuum was applied through a central vacuum system.

At the end of each cropping season soil samples were taken within each plot at 20 cm depth intervals to a depth of 160 cm below the soil surface. Samples were taken at two locations in each plot, and composited for laboratory analysis. The electrical conductivities of saturation extracts of these samples were determined.

At a weather station adjacent to the plot area, measurements were made of the daily incoming radiation, daily wind run, maximum and minimum temperature, relative humidity, rainfall, and pan evaportation.

The irrigation water used in the experiment came from an 8-inch well just outside the plot area, and had the following average concentrations of ions, expressed in meq per 1: Ca^{+2}, 7.73; Mg^{+2}, 1.68; Na^{+}, 5.46; K^{+}, 0.20; Cl^{-}, 2.53; HCO^{-}_{3}, 5.16; $SO^{=}_{4}$, 5.56; NO^{-}_{3}, 0.01. The water had an average EC of 1.22 mmhos/cm.

RESULTS

Table 1 presents the potential gradients, averaged for all plots, as measured in the sandy subsoil of the plots during the 1972 and 1973 growing seasons.

At all times and for all plots the hydraulic gradients in the subsoil were near minus one, as expected, and directed downwards, indicating some downward movement of water. With these gradients and values of the hydraulic conductivity (Kθ)), drainage rates may be calculated. However, values of the hydraulic conductivity, determined during transient drainage experiments on three plots, showed large variations with water content in the subsoil (Wierenga, 1977). Furthermore, subsoil water contents varied greatly between plots. For example, the mean water content at the 120 to 150 cm depth for all plots during the 1973 irrigation season was 0.125 cm^3/cm^3 with a standard deviation of 0.04 cm^3/cm^3. The large variation in subsoil water contents, the steepness of the hydraulic-conductivity versus water content relationships, (K(θ)), and the errors in water content measurements, as well as in the determination of the hydraulic conductivity values (the latter could be more than 100% in the range of interest here (Flühler, et al. 1976), made it difficult to obtain reliable drainage fluxes on the basis of K(θ) relationships determined for three plots only. For these reasons, the total volume of return flow during each season was estimated as the difference between irrigation water applied and estimated consumptive use. Consumptive use was estimated from weather data with empirical coefficients for computing actual evapotranspiration from potential evapotranspiration (Wierenga, 1977).

TABLE 1

Hydraulic gradients (cm/cm), averaged for all plots and for each month, during the 1972 and 1973 growing seasons. Each number is the average of 450 observations.

	1972	*1973*
June	-0.86	-0.61
July	-1.10	-0.70
August	-0.84	-0.90
September	-0.58	-0.76

An analysis of variance of the estimated drainage losses showed significant differences due to efficiency and depletion treatments. Differences among depletion treatments, although very small, were not intended, but resulted from timing of irrigations and the cut-off date of irrigations near the end of August.

An important soil physical property influencing salt retention in a soil is field capacity. Field capacity was estimated for each plot as the total water held in the soil profile immediately following preirrigation. The variation among the field capacities were investigated with an analysis of variance. It was established that the field capacity values were uniformly distributed among the treatments, with a coefficient of variation of ±16% from a mean value of 38.4 cm of water.

Analysis of variance of the field capacity and drainage losses indicated that the experiment was effectively carried out as designed and that field capacity was distributed uniformly among the irrigation treatments.

The quality of return flow was estimated from soil solution samples obtained through suction cups, and also from saturation extracts of soil samples removed from the 140-160 cm depth under each plot. The mean electrical conductivities of soil solution samples extracted during the 1972, 1974 and 1974 growing season were 8.10, 7.89 and 7.63 mmhos/cm, respectively. The mean electrical conductivity of the irrigation water during these years was 1.22 mmhos/cm. Thus, on the average, the ratio EC irrigation water/EC drainage water was 6.5. An analysis of variance was made for the electrical conductivities of the soil solution samples collected during the three years of the study. This analysis showed no significant changes between 1972 and 1974 in the quality of return flow, as measured on soil solution samples from the 130-160 cm depth. The only significant effects of irrigation treatments on the concentration of soil solution were the depletion treatments. The treatment means for depletions are presented in Table 2. Table 2 shows that for the combined years the mean EC of the soil solution below the 75 percent depletion plots was significantly lower than the EC of the soil solution below the 25 and 50 percent depletion plots, indicating enhanced leaching by less frequent irrigation, but using the same total amount of leaching water. Care should be taken in interpreting the results, since there was much variation in the EC of the soil solutions extracted from the subsoil of each plot, as well as in the EC's of the saturation extracts.

Figures 1-3 present frequency distributions of the electrical conductivity of the saturation extracts multiplied by percent saturation for samples taken in 20 cm depth intervals to 160 cm from each plot. The EC_e x percent saturation values were plotted versus their relative cumulative frequency on normal probability paper. The EC_e values were multiplied by percent saturation to reduce errors in the preparation of saturation pastes between years.

TABLE 2

Treatment means of the electrical conductivities (mmhos/cm) of the soil solution samples extracted through suction cups in 1972, 1973 and 1974.

	% Depletion			*All*
	25	*50*	*75*	*depletions*
1972	9.73	9.12	5.44	8.10
1973	8.70	7.80	7.17	7.89
1974	6.84	9.53	6.53	7.63
Mean	8.42[a]	8.82[a]	6.38[b]	7.87

a,b — Numbers followed by common letter not significantly different

For a normal distribution of the EC_e x percent saturation values the symbols should follow a straight line. The logarithms of the EC_e x percent saturation values were also plotted. Fig. 1 presents distributions for all depths, while Fig. 2 and Fig. 3 represent distributions for the 0-20 and 140-160 cm depths, respectively. When all depths were considered simultaneously (Fig. 1) the frequency distributions were not linear, but showed linear sections, indicating the presence of two or more soil populations, attributable to extensive soil layering at the site (clay over sand with greatly varying depths of clay). The frequency distributions of the $\log_{10}$ (EC x % saturation) values for the 0-20 cm depth was nearly linear (Fig. 2), indicating a log normal distribution of the EC_e values at that depth. At 140-160 cm, neither of the two frequency distributions presented were linear. Since the variation in depth to sand was particularly great in the third replicate, frequency distributions were also constructed for the EC_e values from the first two replicates only (not presented here). By eliminating replicate 3, the frequency distribution of the values of EC_e x percent saturation appeared to be closer to a straight line, indicating that the bimodal distributions in Fig. 3 were caused to some degree by nonuniformity of the soil in replicate 3. However, it is not clear what causes the EC_e x percent saturation values at the 0-20 cm and 140-160 cm depths to be other than normally distributed. The implications of log normal distributions of soil salinity values on the quality of return flow have not yet been fully investigated.

An analysis of variance was also made on the soluble salt content of the soil in each plot.

The soluble salt content of the soil in each layer, expressed in g/100 g soil or percent salt, was computed from the EC_e of each layer. The coefficient for computing soluble salt content from the EC_e was obtained by analyzing one set of samples for anions and cations, and using the equivalent weights of these ions as well as the saturation percentage of each sample. No significant effects of treatments on the salt contents in the soil were found. The only factors which had a significant effect on soil salinity were depth and the year x depletion interaction. The significant variation by depth was expected, since the soil profiles were sharply stratified. The large spatial variation in soil salinity (Fig. 2 and 3) was not expected, however. An index of variation is the standard deviation of the mean soil salinity. For depths greater than 100 cm, the standard deviation was typically as large as the mean. In general, spatial variation in EC_e and salt content appeared to be greater in the subsoil than in the topsoil. This was also evident when Figures 2 and 3 were compared. Soil salinity was independent of the efficiency treatments, which was not too surprising considering the relatively small differences in the amounts of water applied on the three efficiency treatments, and the extreme natural variability of the experimental site. Table 3 summarizes the data on soluble salt content in the soil, determined from saturation extracts.

TABLE 3

Mean soluble salt contents (g/100 g of soil), estimated from saturation extracts, by depth for each sampling period.

	Depth (cm)								*All*
	0-20	*20-40*	*40-60*	*60-80*	*80-100*	*100-120*	*120-140*	*140-160*	*dep.*
Control	.20	.25	.33	.20	.15	.10	.07	.04	.17
Fall '72	.12	.19	.36	.30	.16	.11	.08	.06	.17
Fall '73	.13	.17	.35	.33	.17	.12	.09	.07	.18
Fall '74	.13	.23	.34	.36	.19	.12	.08	.06	.19

The data in Table 3 show a large increase in soluble salt content to about 0.3 g/100 g at 80 cm and then a decrease to .06 g/100 g at 160 cm. For most of the plots, the clay/sand interface was approximately at 70 to 80 cm, although there was much deviation. Thus, it appears that extensive accumulation of salt at or above the clay/sand interface has taken place over the years. During the three years of the experiment, the salt concentration in the surface soil was lower than in the control, while the salt concentrations at 60-80 cm showed an increase. The salt content averaged over all depths showed a slight increase between 1972 and 1974. However, the increase is relatively small, e.g. from 0.17 g/100 g to 0.19 g/100 g, or about 10%.

SUMMARY AND CONCLUSIONS

The results of this study showed that, for our conditions, soil salinity and quality of irrigation return flow were relatively insensitive to irrigation efficiency and leaching treatments, over a three-year period. The salt concentration of the soil solution of the sandy subsoil did not vary significantly during the experimental period. The same was true for the salt concentration in the saturation extracts of soil samples removed from the sandy subsoil.

Observations similar to ours were made by Bliesner et al. (1977), who found insignificant increases in average salinity in soil profiles irrigated with water having EC's of 0.90, 2.22 and 2.80 mmhos/cm, respectively, and leaching fractions varying between .003 and .343. In order to predict salinity profiles in such soils, Hanks et al. (1976) developed a model with an empirical source-sink term to account for the behavior of precipitated salts in the soil system and the lack of changes in profile salinity under different leaching practices. Although the chemical precipitation of salts was not studied here, it was possible that precipitation and dissolution of soil salts were important factors in our soils. This was indicated by the apparent accumulation of salt near the clay-sand interface.

The spatial variability of soil salinity in the soil of this study greatly complicated the assess-

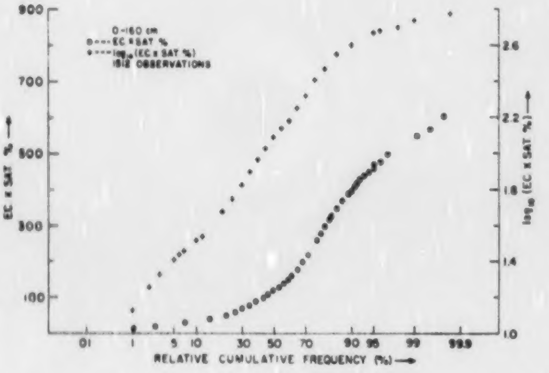

Figure 1. Relative cumulative frequency of EC_e (mmhos/cm) x saturation (%) for the 0-160 cm depth.

ment of the effects of irrigation treatments on soil salinity. Spatial variablility in soil salinity was caused by differences in soil profile characteristics, but may also have been related to local variations in leaching patterns, which were observed at the site (van der Pol, et al., 1977). Refined statistical techniques will have to be used to determine the effects of treatments under our field conditions.

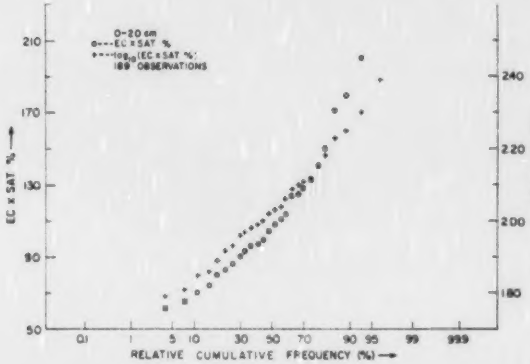

Figure 2. Relative cumulative frequency of EC_e (mmhos/cm) x saturation (%) for the 0-20 cm depth.

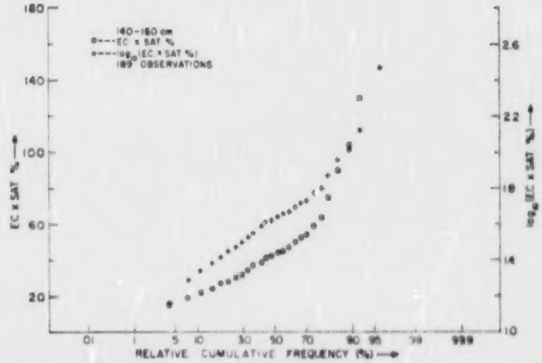

Figure 3. Relative cumulative frequency of EC_e (mmhos/cm) x saturation (%) for the 140-160 cm depth.

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Effect of Irrigation Systems on Water Use Efficiency and Soil-Water Solute Concentrations

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ABSTRACT

The effect of sprinkler irrigation (Sp), furrow irrigation (F), subirrigation (Su), and automated subirrigation (ASu) systems on water use efficiency and soil-water solute concentration was evaluated at a field site in Knox County, Texas. Significant differences existed in the irrigation water requirement of sweet corn irrigated by the different systems (F > Sp ≅ Su > ASu). However, little difference in total water requirement existed between systems — the soil water was utilized more efficiently (ASu > Su ≅ Sp > F). Automation of irrigation systems offers the possibility of significantly enhancing irrigation water use efficiency of supplemental irrigated areas.

Soil-water solute concentrations were too low to be of concern relative to degrading the quality of irrigation return flows due to the dilution effect of rainfall. The relative ranking of the different irrigation systems for the various solutes was:

***Chloride** - F > Sp > Su > ASu*
***Sulfate** - F > Sp ≅ Su > ASu*
***Sodium** - Su > F > Sp > ASu*
***Calcium** - F > Sp > Su > ASu*
***Magnesium** - Sp > F > Su > ASu*
***Potassium** - Sp > Su > ASu > F*
***Ammonium** - ASu > Su > Sp > F*
***Conductivity** - Sp > F > Su > ASu*

In most cases, at depths below 3.0 m, the concentrations of the above solutes in the soil were less than those of the irrigation water.

Although soil-water solutes were not a problem in the irrigation return flows, the lower concentrations of the ASu and Su systems indicate that they may be superior to F and Sp systems in maintaining the quality of irrigation return flows where solutes are a problem.

INTRODUCTION

In 1970, a cooperative project was initiated between the Environmental Protection Agency and the Texas Agricultural Experiment Station. The major emphasis of the study was to determine if current irrigation and fertilization practices were contributing to the increasing nitrate of the ground water and to develop management practices, if it was determined that fertilizers were a major contributor to the nitrate in the water table. The results of these studies are reported in a paper in the Nitrogen in Return Flows section of this conference.

Also included in the study was an evaluation of the influence of sprinkler irrigation, furrow irrigation, subirrigation, and automated subirrigation on water use efficiency and soil-water solute concentration. It is the purpose of this paper to summarize the results of these studies.

METHODS AND MATERIALS

The study was conducted on a Miles loamy fine sand (Udic Paleustalfs) located in Knox County, Texas. Four types of irrigation systems were evaluated in the study: sprinkler irrigation (Sp), furrow irrigation (F), manual subirriga-

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tion (Su) and automated subirrigation (ASu). The pipe of the subirrigation systems was located at a depth of 30 cm and spaced 102 cm apart. A total of 45 plots were available for various aspects of the study. The plots of each system were 16 102-cm rows wide and 60.8 m long. Details concerning the irrigation system design have been previously described in other publications (7) (8).

The meteorological equipment necessary to estimate evapotranspiration potential (ET_p) according to the method of Jensen et al (4) was located at the site. To determine leaf area index (LAI) on the plots, a relationship between leaf area and stem diameter of the corn was derived so that leaf area measurements of a large number of plants could be made.

The generalized water budget model used in comparison was:

$$\Delta W = M + Ir - N - F - (E+T) \qquad [\text{Hillel (3)}]$$

where Δ = change in water content, M = precipitation, Ir = irrigation water, N = runoff, F = deep percolation, E+T = evaporation + transpiration.

During the growing season, there was no runoff from the plots. Also, the location of peak concentrations of a bromide tracer in the root zone remained nearly constant during the growing season indicating that there was negligible deep percolation during the study period (5). Since there was no runoff or deep percolation from the plots, the above equation became $ET = M + Ir - \Delta W$. Precipitation (M) was measured with a weighing rain gauge, Ir with meters and ΔW with calibrated neutron probe.

Water was applied when the potential at 30 cm decreased to -40 cb in the Sp, F, and Su plots. Due to the porosity of the loamy fine sand soils, it was not possible to apply less than 76 mm of irrigation water per application with the F system. In the Sp and Su plots, it was possible to apply a percentage of ET_p at each application varying according to the LAI-evapotranspiration relationship presented by Ritchie and Burnett (6). Water was applied as needed to the ASu plots when the potential decreased to -40 cm until the potential increased above -40 cb.

Sweet corn [(*Zea mays* L.) var. Bonanza] was grown on the plots and treated with cultural practices necessary to assure adequate growth and yield. All plots were fertilizeed with 112 kg of nitrogen/ha. Eight replications of yield data were obtained from each irrigation system.

A soil-water extraction system was installed to obtain samples for solute analyses. The extraction system was composed of vacuum pumps connected by an underground line to sampling bottles and soil-water extraction tubes. One problem that occurred was the evaporation of water from the collection bottles. This was eliminated by adding mineral oil to the bottles.

Chemical analyses on the extracts included nitrite, nitrate, chloride, ammonium, orthophosphate, sulfate, calcium, sodium, potassium, magnesium and conductivity. Procedures used in the analyses for the ions using an Auto-Analyzer have been previously described (8).

RESULTS AND DISCUSSION

Water Use Efficiency

Water use and yield of sweet corn in the study are shown in Table 1. If only the irrigation water data are considered, it would appear that a breakthrough in the amount of water required by sweet corn occurred. Essentially the same yield of sweet corn was obtained when 142 mm of irrigation water were applied with ASu, 248 mm with Su and Sp, and 351 mm with F. However, when the significant differences in change in soil-water content in the soil profile are considered, there was no significant difference in the consumptive use (CU) of the crop (F = 361 mm, Sp = 346 mm, Su = 340 mm, ASu = 300 mm). These data thus support the fact that irrigation systems do not change greatly the CU of crops, previously pointed out by Bucks et al (1) (2).

Also included in the table are the number of irrigations applied with each system. Three irrigations were applied with the Su system and 5 irrigations were applied with F and Sp systems. In the plots with ASu, 25 applications were applied. In general, the amounts applied with the ASu system were in the range of the amounts received in showers from rainfall.

Automation of irrigation systems does afford the possibility of making more efficient use of water stored in soil profiles. This factor should not be discounted in those areas where supplemental irrigation rather than full irrigation is used. A zone of lower moisture content

TABLE 1

Water applied* and yield of sweet corn irrigated by various irrigation systems comparing the water use efficiency of irrigation systems in Knox County, Texas, 1973.

*Irrigation System***	*Irrigation Water Applied*	*Number of Irrigations*	*Soil Water Content Change During the Growing Season*	*Total Water Consumptive Use (CU) of the Crop*	*Yield***
	(mm)		*(mm)*	*(mm)*	(ears/ha)
F	351 a	5	-10 a	361 a	38,918 a
Sp	248 b	5	-98 b	346 a	40,154 a
Su	248 b	3	-92 b	340 a	43,242 a
ASu	142 c	25	-168 c	300 a	39,536 a

*Numbers not followed by the same letter are significantly different at the 5% level of probability.
**F = Furrow, Su = Subirrigation, ASu = Automated Subirrigation.
***A total of 83 mm of rainfall was received on 13 days during the growing season.

can be developed to store rainfall, yet the crop can obtain adequate moisture and not become stressed. Automation of F and Sp systems deserves further investigation as a means of increasing application efficiency. Irrigation return flow can be reduced in those areas that do not require a leaching requirement either by automating systems or by using a measure of ET_p as a basis of irrigation. However, in most irrigated areas, leaching requirements could be provided by automated systems or included with the ET_p.

The concept of irrigating only a portion of the root zone in supplemental irrigated areas using current irrigation systems so as to leave a portion for storage of rainfall to obtain more efficient utilization of irrigation water needs to be evaluated. Some approaches to this would be to irrigate every other furrow with furrow irrigation systems and apply smaller amounts more frequently with sprinkler irrigation systems. Producers are using these practices to a certain extent but they could be further refined to increase irrigation water efficiency.

Soil-Water Solutes

Nitrite

Analyses for nitrite from samples obtained during the first year of the study showed that 0.1 mg/l or less existed in the soil; therefore, analyses were not continued.

Phosphate (Orthophosphate)

Concentrations of orthophosphate of the extracts were generally less than 1 mg/l ranging primarily from 0 to 0.3 mg/l. Such concentrations of phosphate are no problem relative to the water quality of irrigation return flows. Phosphate analyses were, therefore, discontinued after the first year of the study.

Chloride

Changes in chloride concentrations in soil-water extracts over a two-year period (1971-1973) are given in Table 2. There was a general increase in chloride concentration in the Sp system between 1971 and 1972 and between 1.2 and 3.0 m to concentrations greater than those of the irrigation water. Between 1971 and 1972 growing seasons, 329 mm of rainfall were received in 25 different rainfall periods. This rainfall was apparently adequate to move chloride down in the profile but not out of the profile. In 1973, the chloride concentration was much lower than in the second year of the study. This was due to rainfall received between the 1972 and 1973 growing seasons. The 707 mm received in 40 rainfall periods was adequate to decrease the chloride content below that of the irrigation water throughout the profile.

The same trend was followed in the F system between the surface and 3.0 m in that the chloride content of the extracts decreased between 1971 and 1972-73 to a depth of 3.0 m. Data below 3.0 m were sketchy due to the previously mentioned problems of obtaining soil-water extracts. There was a consistent increase at 7.5 m. However, these samples were from within the water table and it is difficult to ascertain the separate contributions from the

TABLE 2

Chloride concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 73 mg/l)

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1972*	*1973*
0.15	107	10	60	26	60	85	21	73	66	20	93
0.30	113	82	56	97	93	87	75	47	15	39	12
0.45	90	46	17	90	46	77	94	73	63	46	21
0.60	28	64	33	74	51	43	31	10	3	43	10
0.90	15	104	10	88	53	53	83	55	43	46	15
1.20	66	105	14	81	27	14	77	42	10	53	19
1.50	76	107	5	79	25	17	67	23	14	61	7
1.80	23	103	12	49	39	28	62	76	28	24	12
2.10	10	27	17	—	—	37	42	86	—	—	—
2.40	12	93	5	33	—	48	—	70	10	15	—
2.70	4	—	51	40	74	24	28	78	48	—	26
3.00	—	117	—	—	—	—	59	81	12	14	56
4.50	—	49	43	—	—	79	78	42	48	5	10
6.00	—	37	48	—	—	—	—	95	43	58	19
7.50	131	134	33	33	68	101	98	121	53	61	38
9.00	116	72	82	25	22	56	69	86	71	63	43

water table and leaching through the soil profile.

In the Su system, there was a general increase in the chloride concentration immediately at the surface with a major decrease at 0.6 m where the Su system had a major influence. This decrease was apparent down to 1.5 m. At some depths (1.8 m, 2.1 m, 2.7 m, 3.0 m, 7.5 m, 9.0 m), there was an increase in the chloride content during 1972 — but a decrease in 1973. The decreases were probably due to the large amount of rainfall (707 mm) received between the two growing seasons.

The ASu system was similar to the Su system. There was an increase in the surface, a general decrease down to about 2.7 m, a slight increase from 3.0 to 4.5 m and then a general decrease from 6.0 to 9.0 between the years 1972 and 1973.

In summary, there was a major decrease in the chloride content of soil-water extracts between 1971 and 1973. Rainfall received (707 mm) between 1972 and 1973 was apparently a major factor in improving the quality of the extracts. The ranking relative to chloride concentration of the soil profile was F > Sp > Su > ASu. The lower chloride content of the ASu system may have been due to the fact that less chloride was added since less irrigation water was applied. No major accumulations of chloride were noted under any of the systems. Chloride concentrations were generally less than the irrigation water at the end of the three years. It was, therefore, concluded that, under the conditions of this study, chloride would not be a major pollutant of the water table.

Sulfate

The changes that occurred in sulfate concentrations from 1971 to 1973 in the irrigation systems are shown in Table 3. The sulfate concentrations of extracts from plots irrigated with the Sp system exceeded those of the irrigation water in 1971 at 0.15, 0.30, 0.45, 2.7 and 9.0 m. During 1972 and 1973, the concentrations in the surface 0.6 m fluctuated but were generally lower than the irrigation water and values obtained in 1971. There was an increase in sulfate concentration between 1.5 and 2.7 m compared to the values obtained during 1971. Between 3.0 and 9.0 m the sulfate concentrations were generally lower in 1973 than in 1972. At the end of the three-year period, the soil-water extracts exceeded the concentrations of the irrigation water concentration only at 0.3, 2.1 and 2.4 m. In general, the quality of irrigation return flows was better in 1973 than 1971 in the Sp plots.

Sulfate concentrations of soil-water extracts from the F system show definite changes in peak sulfate concentrations within the surface 3.0 m between years. The peak concentration was at 0.3 to 0.6 m in 1971, 1.2 in 1972 and 1.8 to 2.7 m in 1973. Another peak occurred in 1972 and 1973 at 0.3 m, probably from evaporation of irrigation water. The location of the peak at 2.7 m in the F plot was in the same location as one in the Sp plot. There was little change in the sulfate concentrations below 3.0 m in the F system.

Soil-water extract sulfate concentrations for a Su system were similar to chloride in that there was a constant decrease in the sulfate concentration of the extracts between 1971 and 1973 at 0.6 to 0.9 m. In 1972, there was high concentration of sulfate at 1.8 m and 2.7 to 3.0 m in 1973. Below 3.0 m, there was little change in sulfate concentration between 1971 and 1973. At the end of the three-year period, the sulfate concentration exceeded that of the irrigation water only at 1.8 m, indicating that the quality of the irrigation return flows relative to sulfate was high.

With the exception of the concentration at 0.15 m, the ASu system had by far the lowest sulfate concentrations in the profile. There were

TABLE 3

Sulfate concentration (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 129 mg/l)

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	1971	1972	1973	1971	1972	1973	1971	1972	1973	1972	1973
0.15	284	23	127	30	69	187	80	127	146	35	372
0.30	270	146	137	169	154	204	116	83	51	50	20
0.45	241	60	54	179	75	177	142	123	151	87	30
0.60	44	118	54	176	78	106	103	13	20	46	20
0.90	97	90	57	137	105	94	111	61	34	22	23
1.20	65	86	17	112	199	86	61	114	60	41	51
1.50	63	127	64	117	99	98	75	98	36	50	57
1.80	63	129	53	87	107	204	75	220	27	29	18
2.10	108	149	146	108	—	239	145	132	—	—	—
2.40	67	154	142	278	—	255	—	109	161	23	—
2.70	221	—	35	200	156	209	151	83	128	—	48
3.00	—	55	—	—	—	—	84	123	156	39	45
4.50	—	114	75	—	—	156	73	119	71	87	64
6.00	—	110	82	—	—	—	—	45	114	49	67
7.50	36	15	82	22	13	30	26	13	30	29	51
9.00	183	114	123	32	20	39	41	15	23	27	36

decreases in sulfate concentration at 0.3 to 0.6 m, slight increases at 1.2 and 1.5 m, with little change in concentration occurring below 3.0 m.

In summary, the overall ranking of the sulfate concentration of the soil-water extracts from the profile of the various irrigation systems was **F > Sp ≅ Su > ASu. In most cases** the sulfate concentrations of the extracts were lower than that of the irrigation water indicating the quality of the leachate reaching the water table was high from all systems. It was therefore concluded from this study that sulfate was not a pollution hazard.

Sodium

There was a general increase in sodium concentration between 1971 and 1973 between 0 and 3.0 m in the Sp system (Table 4) except at 1.2 and 1.5 m. Below 3.0 m, there was a decrease in the sodium concentration of the soil-water extracts between 1971 and 1973. Only at 0.15 and 0.60 m did the sodium concentration of the soil-water extracts exceed the concentration of the irrigation water in 1973.

The concentration of sodium in the F system was generally higher than the concentration of the Sp system at the end of the three-year period. The sodium concentration of the extracts from 0.15 to 0.45 m increased between 1971 and 1973 apparently due to evaporation. A peak located at 0.9 m in 1971 apparently moved to 1.2 m in 1972 and 1.5 to 1.8 m in 1973. No significant change occurred in the sodium concentration below 3.0 m during the three years of the study.

Decreases and increases in the Su system were noted in sodium concentration during the three-year period. Decreases were noted between 0.3 and 0.6 m and increases were noted at 0.15 and 0.90 m indicating that the sodium moved above and below the zone of influence of the Su pipe. Similar decreases were noted in chloride (Table 2) and sulfate (Table 3) concentrations. Below 3.0 m there was a decrease in the sodium concentration of the soil-water extracts between 1971 and 1973.

TABLE 4

Sodium concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 92 mg/l)

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	1971	1972	1973	1971	1972	1973	1971	1972	1973	1972	1973
0.15	135	6	127	15	51	101	4	75	122	26	194
0.30	80	29	92	17	89	125	27	21	20	29	69
0.45	17	94	48	40	89	104	89	64	48	20	51
0.60	7	124	101	114	50	92	20	27	14	17	54
0.90	32	66	78	150	62	98	60	61	102	73	105
1.20	96	84	71	92	113	83	115	90	103	103	92
1.50	96	94	63	66	73	116	68	67	113	67	51
1.80	61	97	84	24	63	114	50	116	142	174	48
2.10	17	61	92	—	—	71	35	24	—	—	—
2.40	10	23	54	29	—	71	—	22	45	113	—
2.70	12	—	86	29	26	43	12	7	20	—	95
3.00	—	15	—	—	—	—	11	19	43	58	89
4.50	—	20	14	—	—	23	25	10	14	12	14
6.00	—	38	31	—	—	—	—	19	23	15	20
7.50	135	63	63	109	104	110	66	35	31	23	28
9.00	319	229	25	156	141	150	161	81	69	41	48

A zone of low sodium concentration was also noted in the ASu system at 0.3 to 0.6 m in the zone of influence of the subirrigation pipe with higher concentrations located above (0.15 m) and below (0.90 m). Below 3.0 m there was little change in sodium concentration.

In summary, concentrations of sodium in the soil-water extracts from 0.15 m from all irrigation systems were all higher than those of the irrigation water in 1973. However, there were no deleterious accumulations of sodium in the soil profile during the three years of the study. At the end of the three-year period, the sodium concentration of extracts from below 3.0 m from Sp, Su, and ASu systems was less than that of the irrigation water. Only at 7.5 and 9.0 m was the concentration of sodium from the

F system higher than the irrigation water, and these concentrations did not change during the three years for which soil-water extracts were obtained. Above 3.0 m the sodium concentration from the different systems was greatest in the Su system followed by the F, Sp, and ASu systems. The Su system had low concentrations of sodium between 0.3 and 0.6 m where the system exerted a major influence.

Calcium

Calcium data obtained are shown in Table 5. In the Sp system, increases in the calcium concentration were noted between the surface and 2.7 m between 1971 and 1973. No major changes in calcium concentration were noted below 3.0 m.

TABLE 5

Calcium concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 63 mg/l)

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	1971	1972	1973	1971	1972	1973	1971	1972	1973	1972	1973
0.15	31	30	79	40	66	93	35	80	40	26	186
0.30	45	90	59	43	66	59	74	53	53	49	31
0.45	86	43	50	78	47	59	71	75	67	61	36
0.60	37	50	190	15	52	38	63	38	27	56	38
0.90	27	77	55	15	49	64	77	51	54	25	81
1.20	37	56	48	26	34	31	49	34	43	30	40
1.50	41	66	31	50	72	55	56	53	38	72	38
1.80	50	59	32	35	84	117	59	60	76	51	32
2.10	26	71	59	—	—	101	71	99	—	—	—
2.40	29	93	70	50	—	101	—	176	62	44	—
2.70	60	—	118	43	115	70	79	99	77	—	27
3.00	—	71	—	—	—	—	82	86	57	66	45
4.50	—	87	93	—	—	85	68	89	67	77	52
6.00	—	77	85	—	—	—	—	67	77	76	50
7.50	24	82	57	14	34	40	28	63	64	93	55
9.00	22	28	31	12	22	27	23	31	38	44	45

The primary changes in the F system occurred between 1971 and the last two years of the study. Increases in the calcium concentration of the extracts from 1971 to 1972 between 0.6 and 1.2 m remained stable through 1973. The rains received between 1972 and 1973 apparently did not affect the calcium concentrations as they did the chloride concentrations (Table 2).

Decreases in the calcium concentration in the 0.15- to 0.9-m zone in the Su system were not as great as those of other ions (Tables 2, 3 and 4). A major increase in calcium concentration to 170 mg/l at 2.4 m was noted in 1972. However, in 1973 the calcium concentration of the extracts was approximately equal to that of the irrigation water (63 mg/l) throughout the soil profile.

The ASu system had a low calcium concentration in the zone of influence of the subirrigation pipe (0.30 to 0.61 m). Calcium concentrations increased at 0.15 and 0.90 m in the periphery of the zone of influence of the Su system. Calcium concentrations of extracts below 1.5 m were generally lower in 1973 than in 1972.

In summary, the overall quality of the irrigation return flow with respect to calcium at the end of the three-year period was high. Excluding the surface, the order of calcium concentrations at the end of the three-year period with respect to irrigation systems was R > Sp > Su > ASu. The Sp system had the highest concentrations above 1.5 m while the F system had the highest concentration below 1.5 m. At the end of the three-year period, the calcium concentration of the extracts was approximately equal to that of irrigation water in the Sp, F, Su plots and less than irrigation water in the ASu plots. Since less water was applied through the ASu systems, it appears that the amount of water applied as well as the irrigation system may influence the ion concentration in the profiles below irrigation systems.

Magnesium

Data on magnesium concentration of soil-water extracts from the various irrigation systems are shown in Table 6. These data were obtained only during the 1972 and 1973 crop years. In the Sp system, there was some increase in concentration in the surface at the 0.3 and 0.6 depths. Otherwise, there was a general decrease in the magnesium concentration between the two years. Concentrations of the extracts exceeded those of the irrigation water (42 mg/l) only below 2.7 m.

Concentrations of magnesium in the surface 1.5 m were generally lower in the F system than the Sp system. Increases in magnesium occurred between the surface and 1.2 m in the F system. There was a general overall increase between 1972 and 1973, but the final concentrations in the profile were not as great as they were in the Sp system.

In the Su system, the pattern of the magnesium concentrations were similar to those obtained for other ions (Tables 2, 3, 4 and 5) in that there was a decrease at 0.6 m in the major zone of influence of the Su system. With the exception of the 0.15-m depth, the magnesium concentrations generally decreased throughout the profile in the Su and ASu systems.

In summary, the Sp plots had the highest magnesium concentrations followed by the F plots with the Su and ASu plots being the lowest. In general, the magnesium concentrations of the soil extracts from the root zone tended to be lower than the concentrations of the irrigation water while the calcium concentrations tended to be higher than those of the irrigation water. This suggests that a portion of the magnesium applied in the irrigation water was absorbed by the clays or precipitated to a less soluble form.

Potassium

Potassium concentrations obtained during the course of the study are shown in Table 7. A decrease in potassium concentrations above 0.9 m between 1971 and 1973 was noted in the Sp system. There is some indication of a tendency toward slight accumulations in the lower part of the profile during 1972 between 1.5 and 1.8 m. However, these concentrations were not noted in 1973. The concentrations were higher at 0.6 m in 1973 than they were in 1971 indicating the possibility of leaching. However, below 18 m the concentrations were slightly less or approximately equal to those of the irrigation water following the first year of the study. No massive amounts of leaching were occurring compared to the amounts produced in the surface, indicating that the excess potassium may have reacted with the clay.

TABLE 6

Magnesium concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 42 mg/l)

Depth	*Sprinkler*		*Furrow*		*Manual Subirrigation*		*Automated Subirrigation*	
(m)	*1972*	*1973*	*1972*	*1973*	*1972*	*1973*	*1972*	*1973*
0.15	25	39	24	30	19	23	11	133
0.30	29	43	18	31	18	17	18	8
0.45	17	15	13	26	25	28	19	9
0.60	14	41	14	15	12	7	20	8
0.90	35	13	11	18	15	17	17	18
1.20	45	29	10	10	12	9	20	12
1.50	27	7	35	13	11	29	25	9
1.80	35	7	44	52	22	58	34	19
2.10	46	27	—	42	36	—	—	—
2.40	48	25	—	49	27	6	31	—
2.70	—	58	43	36	29	25	—	18
3.00	59	—	—	—	30	20	44	32
4.50	43	27	—	52	45	35	52	42
6.00	46	48	—	—	48	37	47	40
7.50	40	32	11	13	34	31	33	29
9.00	13	10	8	8	19	17	26	22

TABLE 7

Potassium concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration - 2.8 mg/l

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1972*	*1973*
0.15	29.2	12.0	21.0	11.4	.0	10.4	28.2	15.5	15.2	13.3	23.7
0.30	32.9	23.7	6.3	6.4	3.0	6.3	28.5	21.3	16.3	15.0	12.4
0.45	29.8	18.5	16.5	1.6	2.0	3.2	25.4	13.5	11.4	7.2	7.3
0.60	9.7	9.2	22.7	2.1	1.0	2.1	6.1	9.7	4.2	9.2	6.3
0.90	1.6	5.1	5.2	2.1	1.0	2.1	6.6	4.0	9.5	6.2	12.5
1.20	1.1	4.2	5.5	1.1	1.0	1.1	3.0	2.1	9.2	2.1	4.2
1.50	2.2	3.0	2.1	0.0	4.9	1.1	3.1	1.1	10.6	3.1	3.2
1.80	1.6	6.0	2.1	0.0	3.3	0.5	3.1	2.1	10.9	10.6	3.2
2.10	1.6	6.0	2.1	—	—	5.5	3.0	1.1	—	—	—
2.40	1.1	3.0	1.1	1.5	—	5.5	—	3.3	1.1	3.3	—
2.70	2.2	—	0.5	0.0	2.9	2.1	1.5	1.1	1.1	—	2.1
3.00	—	0.0	—	—	—	—	1.0	1.1	2.1	5.5	4.2
4.50	—	2.0	1.1	—	—	1.1	2.0	1.1	2.1	1.1	1.1
6.00	—	1.0	1.1	—	—	—	—	2.1	2.1	2.1	2.1
7.50	6.5	1.0	1.1	0.0	1.0	1.1	2.5	2.1	3.2	1.1	1.1
9.00	8.1	3.0	2.1	0.0	1.0	2.1	5.1	3.0	3.2	2.1	2.1

There was little change in potassium concentration in extracts from the F system between 1971 and 1973. This plot was land leveled; consequently, part of the micaceous minerals which were high in potassium were probably removed from the surface and the potassium in solution in the resulting top soil is not as great as the top soil which was removed. In general, the potassium concentrations below 1.5 m were approximately equal to that of the irrigation water (2.8 mg/l).

The Su system yielded data very similar to the Sp system in that there was a decrease in the potassium concentration at the surface between 1971 and 1973. There was a slight increase at 1.5 to 1.8 m indicating some movement out of the zone around the subirrigation pipe to this particular area. The decreases in the surface were greater than that of the Sp plots indicating that the surface may have been drier with less moisture available to make the potassium available.

The same trend holds for the ASu system in that the surface remained higher with a zone of low concentration at 0.6 m. There was some indication that there was an increase in potassium concentrations at 0.9 to 1.8 m, indicating again some movement out of the zone where the subirrigation pipe was located.

In summary, the greatest potassium concentrations were in the plots with a Sp system followed by the Su, ASu, and F systems. Soil minerals are indicated to play a major role in the production of potassium in that the land leveled F system had very low potassium concentrations in the soil solution.

Ammonium

Typical ammonium-N concentrations found during the course of the study are shown in Table 8. Significant amounts of ammonium were found periodically in extracts from all systems, i.e., at 9.0 m in 1971 in the Sp system, 2.7 m in 1972 in the F system, 9.0 m in 1971 in the Su system and 3.0 m in 1972 in the ASu system. Overall, the ranking relative to occurrence of ammonium was ASu > Su > Sp > F. While there was some evidence of ammonium-N in the profile below the root zone, the inconsistency with which it was found in concentrations above 3.0 mg/l makes assessment of movement impossible. Generally, ammonium-N concentrations were uniformly low and would appear to be of little consequence from the standpoint of irrigation return flow degradation.

Conductivity

Between 1971 and 1973, the conductivity of soil-water extracts from 0.6 and 0.9 m (Table 9) increased in the Sp system. Otherwise, there was a general decrease in the extracts. There was little discernible change in conductivity of soil-water extracts of the F system. In both the Su and ASu systems an increase in conductivity of extracts from 0.15 m and a decrease from 0.3 to 0.9 m occurred in the zone of influence of the Su system. Otherwise the conductivity of the extracts from the remainder of the profile remained stable or decreased.

In summary, the conductivity was highest in the Sp system followed by F, Su, and ASu systems. Most values were lower than the average irrigation water conductivity of 947 μmhos. This is not surprising since the area is a supplemental irrigated area and rainfall is a major factor influencing the conductivity of soil-water extracts. The conductivity data thus indicate that the salt load of the irrigation return flow in this study was not a problem.

TABLE 8

Ammonium concentrations (mg/l) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Irrigation water concentration < 1mg/l)

Depth	*Sprinkler*			*Manual Furrow*			*Automated Subirrigation*			*Subirrigation*	
(m)	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1972*	*1973*
0.15	2.1	0.3	1.1	0.3	0.4	0.2	0.2	4.9	0.5	10.2	1.7
0.30	0.7	0.3	0.5	0.3	0.5	0.0	1.5	0.8	0.5	4.1	1.7
0.45	0.2	0.4	0.5	0.6	0.6	0.2	1.6	0.3	0.2	0.7	0.7
0.60	0.1	0.1	0.5	0.3	0.8	0.5	0.6	1.0	0.5	1.5	2.0
0.90	1.7	4.9	1.5	0.3	0.4	0.2	1.2	2.5	0.7	5.5	2.4
1.20	0.4	1.2	1.1	0.2	0.7	0.2	1.8	1.9	1.1	1.1	3.4
1.50	0.2	2.0	0.2	1.5	2.0	0.7	1.2	2.5	3.6	1.2	1.2
1.80	0.2	3.9	0.2	1.2	1.1	2.3	1.6	1.1	2.3	19.5	1.1
2.10	1.3	1.2	0.2	—	—	3.6	3.3	1.2	—	—	—
2.40	0.5	1.4	0.2	3.0	—	2.4	—	7.2	0.0	8.1	—
2.70	0.7	—	9.7	3.0	5.7	0.5	0.2	1.5	0.5	—	0.5
3.00	—	2.4	—	—	—	—	0.4	2.3	0.5	32.5	3.4
4.50	—	2.5	0.2	—	—	0.2	2.6	4.6	0.2	1.2	1.0
6.00	—	1.6	0.0	—	—	—	—	1.5	0.2	2.5	1.0
7.50	6.0	0.3	0.2	0.8	0.6	0.2	3.0	0.5	0.2	0.4	0.5
9.00	10.5	5.1	0.5	1.7	2.8	6.2	10.0	5.7	0.5	7.4	1.0

CONCLUSIONS

1. The ASu systems are superior to Su and Sp systems which are superior to F systems in the amount of irrigation water required to produce corn even if the manual systems applications are scheduled based on ET_p.

2. No significant differences in total water requirement of corn were noted between the various irrigation systems. The soil water was used more efficiently when less irrigation water was applied.

3. Supplemental irrigated areas can increase irrigation water-use efficiency significantly by utilizing systems so that a portion of the root zone remains dry for the storage of rainfall.

4. The data indicate that the quality of irrigation return flows of Su systems will be superior to F and Sp systems because the concentrations of all solutes and the electrical conductivity (EC) were lower.

5. A zone low in all solutes is formed in the path of water flow around the subirrigation pipe.

6. Because salts are moved upward from subirrigation emitters, periodic supplemental leaching with another system may be needed in arid areas.

TABLE 9

Conductivity (μmhos) of porous bulb soil-water extracts from various depths 1971-73 from different irrigation systems located on a Miles loamy fine sand, Knox County, Texas. (Conductivity of irrigation water - 947 μmhos)

Depth	*Sprinkler*			*Furrow*			*Manual Subirrigation*			*Automated Subirrigation*	
(m)	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*	*1972*	*1973*
0.15	1335	260	550	530	760	990	660	800	935	450	1225
0.30	1124	860	922	820	890	980	710	600	345	560	330
0.45	1069	850	850	1100	720	895	835	840	800	590	360
0.60	700	930	1575	940	640	660	550	360	305	650	510
0.90	630	920	825	970	670	850	700	660	325	580	555
1.20	860	940	175	840	760	560	810	650	410	860	420
1.50	904	960	500	960	320	840	710	550	190	740	550
1.80	740	395	600	770	340	130	640	950	135	1185	630
2.10	660	340	255	—	—	220	810	970	—	—	—
2.40	—	845	760	975	—	240	—	350	670	310	—
2.70	555	—	290	865	270	705	530	700	710	—	730
3.00	—	300	—	—	—	—	555	670	660	200	—
4.50	—	800	670	—	—	750	645	670	680	560	550
6.00	—	879	795	—	—	—	—	760	760	620	570
7.50	1085	980	710	580	630	650	672	700	690	580	560
9.00	1595	1180	—	715	670	670	815	630	700	570	560

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Scientific Irrigation Scheduling for Salinity Control of Irrigation Return Flow

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ABSTRACT

Basic principles of irrigation water management and irrigation scheduling are presented. Commercial and agency groups expanded rapidly in the 1970's providing field-by-field scheduling services to over 600,000 acres in 1976.

The leaching fraction used on projects can effect return flow quality. Most leaching fraction/return flow models hypothetically assume uniform water applications of exact quantities to attain targeted leaching fractions. The average or effective leaching fraction for a field is dependent on the irrigation uniformity coefficient. The effects of nonuniform water application on average leaching fractions will be presented, along with the probable effects of expected improvements in irrigation efficiency on return flow. Also, estimates of the accuracies in estimating evapotranspiration and measuring water will be presented. Substantial improvements can be made in irrigation efficiencies before minimum leaching fractions are reached on most western irrigated projects.

INTRODUCTION

The annual return flow volume from an irrigation project is dependent on the annual irrigation water volume diverted to the project, precipitation, and the project evapotranspiration (ET). The average project return flow quality is influenced by precipitation, the quality of the irrigation water, the proportion of irrigation water in the return flow, the integrated project leaching fraction (LF), and salt pick-up. The salt pick-up is influenced by the volume of project deep percolation and seepage from canals and laterals.

The title of this paper implies that the variables affecting the quantity and quality of return flow can be controlled by irrigation scheduling, but the potential degree of control has not been delineated. The purpose of a detailed study conducted in 1975 (Jensen, 1975) was to evaluate the probable effects of implementing scientific irrigation scheduling on return flow quality. The results of that study and another presented at the California Conference on Salt and Salinity Management (Jensen, 1976) are summarized in this paper.

What is Irrigation Scheduling?

Irrigation scheduling is predicting the time and amount of the next irrigation. This process is dependent on the precipitation and ET since the last irrigation, the allowable soil water depletion, and the expected precipitation. Irrigation scheduling can significantly influence the volume of water diverted to a project. Thus, scheduling can potentially influence the LF, and to a limited extent canal seepage. Irrigation scheduling will have little effect on ET when crops are irrigated for maximum, or for optimal yields.

Reducing the salt load from an irrigation project requires a minimum leaching fraction (LF*) permissible for the crops and water quality involved. The average LF will be greatly dependent on the attainable irrigation uniformity. Thus, even though irrigation scheduling technology can be refined and implemented, attaining low average LF's will require both irrigation scheduling and significant improvements in irrigation systems to uniformly apply water.

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Need for Irrigation Scheduling

If the management objective is to minimize the salt load in return flows, then minimum leaching fractions must be achieved on each irrigated field. It is difficult to manage the soil water reservoir of complex soil-crop-climate systems because many variables are involved, and the soil water status is not readily apparent. The quantity of water applied at each irrigation is important because a single overirrigation during a growing season can drastically decrease the seasonal irrigation efficiency and prevent achieving the targeted field LF.

Accurate water control is easier to achieve with irrigation systems that have limited opportunities for overirrigation. With sprinklers, for example, the amount of water applied is controlled by the system and not the soil when the application rate is less than the intake capacity. Thus, a targeted application can be achieved by regulating pressure and hours per set, especially with systems that apply water while moving. Moving systems usually apply water more uniformly than those with stationary heads.

Specific amounts of water can be applied with surface irrigation systems if modern technology is used, but most surface systems are operated today as they have been for the last two or three decades. Stream sizes normally are not increased and set times reduced enough to achieve the targeted uniform irrigation when intake rates change after tillage. Facilities do not permit these detailed changes at each irrigation, especially with older systems that do not have water measuring devices, adjustable water control structures, and lined channels or enclosed distribution systems. The duration of each irrigation set is often based on some convenient period such as 12 or 24 hours because of the labor required to change sets. When coupled with long length of runs, light irrigations are difficult to achieve on most existing surface systems. The time of irrigation can easily be changed with these systems, but controlled water applications will require improved facilities. There is an emerging demand for new innovations, instrumentation, and equipment to modernize surface irrigation systems to meet the 1983 goals of Public Law 92-500 for best available technology to control the quantity and quality of irrigation return flow.

Typically, observed irrigation efficiencies on surface irrigated lands in the U.S. are low. Early studies in the 1890's cited overirrigation as the first and most serious mistake made by early settlers in Wyoming (Buffum, 1892). This situation has not changed much on many older projects. Until recently, only limited progress has been made in modernizing surface irrigation systems because there have been few incentives for change because water costs in most areas are low and represent a relatively small percentage of annual farming cost. Also, excessive water application effects on both crop yield and quality normally are not as apparent as the effects of water deficits and salinity caused by inadequate irrigation.

Most older surface irrigation systems require much labor to be operated efficiently. Increasing labor costs generally have reduced labor input, thus offsetting the effects of improvements in irrigation facilities. Similarly, with low cost nitrogen (N) fertilizer, it has been easier and more economical to compensate for poor water management by applying excess N. New regulations on N in return flows and increasing N costs are now beginning to influence irrigation and fertilizer practices. The costs of correcting drainage problems that emerge after several years of excessive water use are often distributed uniformly to all water users in a project and not just to those using excessive water. Sometimes drainage costs are cost-shared, which in essence subsidizes excessive water use. All of these practices have not been conducive to improving irrigation practices and systems.

Today the ecomonics of irrigation are rapidly changing, and new constraints are emerging. Fertilizer costs are increasing. More important, energy costs are spiraling and the certainty of continuing energy supplies for irrigation is diminishing. These and other emerging economic incentives will have a major impact on irrigation water management practices during the next decade. Pending state and federal return flow regulations, involving both water quantity and quality, coupled with increasing labor and energy costs will be changing irrigation farming objectives. New management technology will be needed for irrigation farming to remain solvent and competive with rainfed agriculture. Increased capital investments will be needed to achieve better water control with less labor, and increased technical skills will be needed to service complex irrigation systems. Farm management must place greater emphasis on maximizing net returns and yield per unit of water and less emphasis on maximizing yield per unit area.

As the amount of irrigation water diverted to irrigation projects approaches the consumptive irrigation water requirement, more accurate consumptive use or ET data will be needed to optimize system operations. The demand for irrigation management services will increase which should stimulate the development of more rapid and ecomonical means for monitoring the soil water content and its distribution on individual fields.

Attainable Irrigation Efficiency and Leaching Fractions

Optimum irrigation water management will require more accurate water applications for both consumptive and nonconsumptive uses. Essential or minimum amounts needed for nonconsumptive uses (frost protection, leaching hydrating a root crop before harvest and seed germination) are easy to specify, but may be difficult to achieve because of nonuniform water distribution inherent with many existing systems. For example, if target minimum LF's of 0.05 to 0.1 were acceptable and the management objective was to maintain these LF's on the 10% of each field that regularly receives the least amount of water, the average LF for the field may be three to five times the mimimum LF when using existing sprinkler systems (Table 1, Jensen, 1975). The areas normally receiving the least amount of water are the lower ends of uniformly graded surface irrigated fields and the area between sprinkler laterals that are not moved during the irrigation season.

The water distribution uniformity within individual fields is an important variable that must be considered in estimating the potential effects of minimum LF's on the quality of return flow. This is a very important variable that cannot be neglected because the relationship between the LF and the precipitation of salts within the root zone is nonlinear. The prospects of achieving cummulative seasonal uniformity coefficients (U_c) that exceed 90% by 1983 is very remote for most projects even though the cummulative U_c increases with successive irrigations.

Another important variable that must be considered, except with automatic systems operated by sensors, is the probable accuracy of applying targeted amounts of water. When using values suggested by Jensen and Wright (1976), the coefficient of variation (estimated standard deviation/drainage, expressed in percent) during a 30-day period is about 10 percent with a LF of 0.5 and an average ET of 6 mm/day (0.24 in./day). It increases to about 50 percent as the LF approaches 0.1 (Table 2). The probable error is even greater with shorter time periods because the standard error in estimating ET decreases proportional to $1/\sqrt{t}$.

TABLE 1

Average leaching fraction (LF) for a field for various targeted minimum LF (LF*) in relation to the uniformity coefficient (U_c) of water applications (From Jensen, 1975).

			Average LF with a LF of:*		
U_c	s	α_d	*0.05*	*0.10*	*0.15*
%	%				
100	0	1.00	0.05	0.10	0.15
95	6.25	.89	.15	.20	.24
90	12.50	.79	.25	.29	.33
85	18.75	.69	.34	.38	.41

Assumptions:

Average depth of water applied in the 10% of a field regularly receiving the lease amount of water is $(1 + LF^*)$ *ET; the application of water by a sprinkler system is normally distributed with a standard deviation,* s*, estimated from the equation* $U_c = [100(1 - 0.8s/100]$*, and is independent of the amount applied; the distribution coefficient,* α_d*, at 5% of the area represents the relative depth of water applied to 10% of the area that receives the least amount of water; irrigations are timed exactly so that only* $LF^*(ET)$ *drains through the soil; and ET is not affected by soil salinity level.*

TABLE 2

Estimated coefficient of variability in applying water to achieve various targeted leaching fractions for 10-, 20-, and 30-day periods (From Jensen and Wright, 1976).

	Period, days		
Target leaching fraction	*10*	*20*	*30*
	%		
0.1	94	58	48
.2	42	27	22
.3	25	16	14
.4	17	11	10
.5	12	8	7

Assumptions:

Mean ET = 6 mm/day (0.24 in./day) estimated from daily climatic data.

Surface runoff (15%) and applied water measured with an accuracy of ± 5%, or $s_Q = 0.025Q$.

Traditional and Modern Irrigation Scheduling Practices

Traditional irrigation scheduling methods are based on tensiometers, electrical resistance units, pan evaporation data, and general fixed irrigation dates and amounts for given crops within a local area. A few farmers now use the neutron probe for measuring soil moisture and scheduling irrigation. Traditional approaches usually require the farmer to use some type of instrument, take soil samples, or use evaporative data. Thus, he must first understand ET and soil moisture depletion. If a tool or instrument is needed he also must understand how it functions and its relationship to the soil water depletion to use it correctly.

Traditionally irrigation scheduling methods have not been very effective in the past, perhaps because there have been insufficient incentives to warrant significant improvements in irrigation management practices. Basically, traditional methods essentially require a "do-it-yourself" approach to irrigation scheduling. Thus, promoting only traditional methods has limited the farmers access to information needed to improve irrigation scheduling decisions. Alternative procedures for providing this information on a real time basis have not been seriously considered, developed and evaluated.

Modern irrigation scheduling services provide farm managers with estimates of the current soil water status on each field, and predicted irrigation dates and amounts to be applied on each field to avoid adverse effects on plant growth. With this information farmers can modify their irrigation practices and schedule irrigations more accurately. The increasing demand for commercial irrigation scheduling services during the past five years is indicative of a long standing need for such information.

A modern irrigation scheduling service (ISS), utilizes the latest irrigation science and technology to provide current information on the available water status in individual fields and projected irrigation dates based on expected climatic conditions. The ISS may provide the daily rate that high frequency systems should apply water to maintain the desired soil water level in each field. When water supplies are limited or another variable, like fertilizer, limits production, the ISS should also recommend the optimum times and irrigation amounts to achieve these goals. An effective ISS recommends needed improvements in irrigation systems to achieve greater irrigation uniformity, reduce water losses, and maintain a favorable salt balance in the soil. Services like these increase the farmer's managerial skills and should increase his net returns (Jensen, 1975).

The irrigation scheduling approach developed by Jensen et al. (1969, 1971) known as the USDA-ARS Computer Program, has been widely accepted because it does not require farmers to obtain technical knowledge and training to apply modern irrigation technology. Periodic updating of the current soil water status, ET rates and projected irrigation dates provide information that greatly increases the farmers' understanding of the soil-plant-atmosphere system. Experience gained in testing this concept in 1968 and 1969 indicated that even though farmers had been irrigating for many years, information provided by this program increased their understanding of processes influencing and controlling this complex system.

Many commercial and agency service groups have adopted the program without change or have modified the USDA-ARS Computer Program to suit their special needs. New commercial firms have been established, and many firms have purchased their own small computers for routine calculations and record keeping on hundreds of fields. The professional staff of an ISS group must be trained in irrigation science and technology for successful application of the program. They must monitor the soil water status and sometimes measure precipitation on each farm to periodically tune the computer results to field conditions. Most companies recommend and provide updated irrigation dates at least weekly. Some fields are inspected twice weekly during the growing season. Some service groups also design improved irrigation systems and provide plant nutrient, pest, control and other services. Service companies must maintain active communications with the farmer, sometimes on a 24 hour basis, and they must have a crew of trained and experienced field technicians. If ISS groups are to provide unbiased recommendations to maximize net returns to the farmer, they should not sell products they recommend. This practice represents a serious potential conflict of interest.

Table 3 is a summary of the general irrigation practices and management options along with the information needed and provided by service groups to improve irrigation management. Such information is needed for all irrigation methods and management options, except, perhaps, fully automated systems that operate with soil-water sensors or a combination of sensors and timed controllers. Periodic monitoring of saline control may still be needed with automatic systems, unless salt sensors are used.

TABLE 3

General irrigation practices and management options and the types of scheduling information needed (from Jensen, 1976).

Irrigation practices and management options	*Types of irrigation scheduling information needed*
A. High frequency	
1. Maintain nearly constant soil water level and target leaching fraction.	Daily evapotranspiration (ET) and rate of water application. Periodic soil water monitoring for content, distribution, and salinity.
2. Planned gradual depletion of available soil water during the crop season with target leaching fraction provided during the noncrop or some other crop season.	Same as for A.1.
3. Combination of A.1 and A.2	Same as for A.1.
B. Normal periodic irrigations	
1. Irrigate to bring the soil to field capacity at each irrigation and provide target leaching fraction.	
a. Constant or fixed application amounts.	Daily ET, earliest next irrigation date permitting efficient irrigation along with the latest next irrigation date to avoid significant adverse effects on crop production. Periodic soil water monitoring for content distribution, and salinity.
b. Fixed irrigation intervals	Daily ET, irrigation amounts for efficient irrigation, and periodic soil water monitoring for content, distribution, and salinity.
2. Planned gradual depletion of soil water during the crop season with target leaching fraction provided during the noncrop or some other crop season.	
a. Constant or fixed application amounts	Same as B.1.a.
b. Fixed irrigation intervals	Same as B.1.b.
3. Combination of B.1 and B.2	Daily ET, earliest next irrigation date and amount for efficient irrigation along with the latest date and corresponding amount to avoid significant adverse effects on crop production and permit efficient irrigation. Periodic soil water monitoring for content, distribution and salinity.
C. Limited and supplemental irrigation	
1. Limited irrigations applied to optimize production or net returns per unit volume of water.	Expected ET, and optimum times and amounts of irrigation considering expected rainfall to maximize production per unit of irrigation water. Periodic soil water monitoring for content and distribution.
2. Alternating shallow, well-watered and deep rooted, nonirrigated crops.	Expected ET and production from alternative sequences.

Monitoring the soil water status in each field may not be required during the entire growing season if excess water is applied at each irrigation, or if the amount of water applied and rainfall are known with reasonable accuracy. However, soil water monitoring is usually required to calibrate or tune the computer calculations, since the error of measuring soil water either gravimetrically or with a neutron probe is generally less than the error in estimating the amount of irrigation water applied. Since the confidence limits of predicted irrigation dates are dominated by the component with the greatest uncertainty, the amount of water applied by surface irrigation systems usually causes the greatest uncertainty and widens the limits until the field can be monitored again.

When irrigation service groups first begin, they provide irrigation schedules without recommending changes in existing systems. Later as they become acquainted with the characteristics and constraints of the systems, and as they and the farmers gain experience, components that need improvemnt can be identified and system improvements scheduled. As labor costs increase, or skilled labor becomes less available, ISS groups will play a more important role in applying modern irrigation science and technology in irrigation water management.

ISS also must be economical, with sufficient accuracy to be compatible with the system's ability to apply specific amounts of irrigation water. Irrigation scheduling information only supplements, and does not replace, the farmers' experience.

Adoption of Irrigation Scheduling Services

Jensen (1975) evaluated ISS provided in 1974 and found that ten western U.S. commercial firms had 1 to 10 years of experience and seven of the ten had five years or less. ISS was provided for a fee to about 4450 fields involving over 100,000 ha (250,000 ac.) of summer crops in eight western states. All 10 firms provided plant nutrition services, seven provided plant pest management services, and six provided engineering services. Technicians, who monitored soil water-depletion in each field once or twice weekly, serviced an average of 5800 acres and traveled an average daily distance of 195 km (120 mi.). Agency or project services were similar to commercial services except the customers paid only part of the direct cost. The balance was distributed uniformly to all water users in the projects. Of 22 agency service groups, 21 had five or less years' experience. These groups provided ISS for about 3500 fields involving 54,000 ha (133,000 ac.) of summer crops in 12 western states. Only about 25% of these groups provided plant nutrition services, 20% provided pest management services, and 15% provided engineering services. Besides field-by-field services, the U.S. Bureau of Reclamation provided weekly estimates for major crops based on early, medium and late planting dates for different general soil types. General irrigation guides for major crops were provided for about 10,000 fields involving about 94,000 ha (233,000 ac.). The Alberta Department of Agriculture in Canada provided ISS to about 140 fields comprising 4,500 ha(11,000 ac.) on a field-by-field basis and provided guides for about 100 fields totaling about 3,200 ha (8,000 ac.).

In 1976, a comparison of seven commercial groups that provided field-by-field services in 1974 and 1976 added over 1,000 fields or 34,000 ha (85,000 ac.) per year. In 1976 ET estimates based on current climatic data were used on 95% of the area served. Most technicians serviced 1,400 to 1,600 ha (3,500 to 4,000 ac.). The capacity of these seven companies in 1976 was only about 6,200 fields or about 174,000 ha (430,000 ac.). These groups could not expand immediately, mainly because of a lack of trained personnel.

Fees varied widely depending on the method of charging. Most prices ranged from $6 to $11 per ha ($2.50 to $4.50 per ac.) for irrigation scheduling, or a flat fee of $175 to $250 per field.

Commercial and agency irrigation scheduling service expanded from less than 40,000 ha (100,000 ac.) on a field-by-field basis in 1971 to over 243,000 ha (600,000 ac.) in 1976. These services are expanding as rapidly as new staff members can be trained and new companies can be established.

The Role Of Irrigation Scheduling and Salinity Control

This assessment of irrigation scheduling and salinity control indicated that substantial improvements in irrigation water management and efficiency can be made before minimal leaching fractions needed to maintain a favorable salt balance in the soil are reached on most western irrigated projects. Only about 10 percentage points improvement in average farm irrigation efficiencies can be expected by 1985 without significantly increasing energy requirements for irrigated agriculture. This change is not expected to significantly influence salinity in return flows except where salt pick-up is a major factor. New emerging ecomonic incentives may bring about more rapid changes.

Continued improvement in irrigation water management is needed, but general implementation of new scheduling technology may require one or more decades. Irrigation system improvements to permit uniform applications of specific amounts of water also will be required. With scientific irrigation scheduling and systems that apply uniform known amounts of water, significant reduction in salt loads in return flows can be achieved. Both components are needed because potential efficiencies of new irrigation systems and salt control probably cannot be achieved without scientific irrigation scheduling.

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Return Flow Management

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Management Guidelines for Controlling Sediments, Nutrients, and Adsorbed Biocides in Irrigation Return Flows

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ABSTRACT

Sediments in irrigation return flows arise mostly from furrow erosion, and nearly all nutrients and biocides in surface irrigation return flows, except those applied directly to the water, are adsorbed to the sediments. Therefore, controlling erosion and sediment loss in these surface return flows also controls the nutrients and biocides. There are three general management approaches for controlling sediments in return flows. The first is to eliminate surface runoff by using irrigation methods that produce no runoff. These methods include properly designed and operated sprinkler systems, basin, trickle, and some border and level furrow methods. The second approach is to eliminate or reduce erosion by controlling the slope in the direction of irrigation, the furrow stream size, the run length, the irrigation frequency and duration, and tillage practices. The third is to remove sediments from surface return flows by controlling the tailwater and utilizing sediment retention basins. All three approaches are applicable and necessary for adequate control in most irrigated areas. Available technology needs to be integrated and applied to these approaches. Research to develop improved irrigation systems and methods, improve irrigation water distribution systems, a better field management practices, an research on design and operational criteria fo sediment retention basins are needed.

INTRODUCTION

Surface irrigation return flow is that portion of the irrigation water applied to soil which passes over the soil surface and becomes runoff. It usually includes direct spill from canals and water that flows through farm ditches but is not applied to the land. Typically, 10 to 30 per cent of the water applied to furrow irrigated land becomes surface runoff. Surface irrigation return flow can also result from irrigation by wild flooding, some border systems and where sprinkle systems apply water more rapidly than the infiltration rate on sloping soils. Only a small portion of the total surface irrigation return flow results from these latter three irrigation methods. No surface runoff results when the water application rate is equal to or less than the infiltration rate. Such application rates can be achieved with properly designed sprinkle irrigation systems and with trickle systems, but the energy requirements of sprinkle systems and the expense of trickle systems limit their use. In contrast to sprinkle irrigation where the entire soil surface is the infiltrating area, only the furrows are the infiltrating area for furrow irrigated land. Furthermore, the furrows also serve as conveyance channels to supply water to the down slope portions of the field. Surface irrigation return flows do not occur with subsurface irrigation or with certain border and furrow methods that confine applied water to a given area, including pumpback systems.

Water passing over the soil surface has limited contact and exposure to the soil at the soil surface, and flow at the interface is into the soil. Therefore, the quantities of soluble salts, fertilizer nutrients and pesticides dissolved or washed off the soil into the water flowing over the soil surface are expected to be extremely small. This is particularly true where water is confined to furrows and contacts only a portion

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of the land surface. Such water does pick up debris, crop residue, applied manure residue, nematodes, plant pathogens and other foreign matter that tends to be floated away by water. When erosion occurs, the most important material picked up is soil and material attached to it. Soil picked up in the erosion process is usually referred to as suspended sediment or sediment.

Erosion of irrigated land has been recognized as a serious problem for many years. Isrealson, et al. (1946) stated that excessive erosion of irrigated lands was adverse to the perpetuation of permanent agriculture in arid regions. Gardner and Lauritzen (1946) reported that it was apparent to every farmer that serious damage resulted when attempting to irrigate steep slopes unless the stream was very small. They recognized that little erosion occurred on lands with gently slopes even with relatively large stream sizes. These observations led them to suggest the vital importance of finding a means to estimate the rate at which soil would erode with various stream sizes at various slopes.

Today, 30 years later, furrow irrigation on steep slopes with stream sizes that are too large, resulting in serious erosion is still commonly observed. Much technology has been developed to control erosion of irrigated land and to reduce sediment concentrations in surface irrigation return flows, but it has not been applied.

There is a need to apply available technology and to develop new technology for reducing erosion and sediment loss from irrigated lands. The purposes of this paper are to provide an overview and an assessment of the problems associated with sediment and adsorbed nutrients and biocides in surface irrigation return flows, to assess currently available technology for implementing control measures, and to suggest research and demonstration needs to develop and apply improved control technology.

Erosion on Irrigated Land

Whenever water flows over cultivated land, erosion may occur. Factors influencing the amount of erosion include: (1) the slope in the direction of irrigation; (2) the stream size; (3) the soil texture; (4) the condition of the soil surface; (5) the duration of the irrigation; and (6) the crop. Most erosion on irrigated land results from furrow irrigation, and basically is erosion of the furrows. Isrealson, et al. (1946) reported that furrows near the head ditches eroded 2.5 to 10 cm in sugarbeet fields. Mech (1959) reported soil losses of 50 metric tons/hectare during a 24-hour irrigation of corn on a fine sandy loam soil on a 7 per cent slope. He further stated that even on relatively flat fields with short runs, 30 cm of surface soil have sometimes been lost after about 10 years of cultivation and irrigation. Similar results have been reported in the 1970's on Portneuf silt loam planted to dry beans, sugarbeets, potatoes and corn.

Each furrow on furrow irrigated land functions as the absorbing surface and as a channel for conducting water to irrigate the remaining length of run (Mech and Smith, 1967). Therefore, the stream size at the head of the furrow must be sufficient to meet the infiltration requirements over the entire furrow length and to propagate the stream to the end of the furrow fast enough to give a reasonably uniform distribution throughout the length of run; ideally, it should not exceed that size. Obviously, larger streams are required to irrigate longer runs. But larger streams have greater energy to erode soils and transport sediment on sloping lands, and thereby cause more erosion. More erosion is expected near the heads of the furrows where runs are long because that is where the stream size is largest. Practically, short irrigation runs have not been used because cross ditches interfere with tillage, seeding, cultivating and harvesting operations. Also, shorter irrigation runs require more labor for irrigation. Also, it is difficult to control stream size so that just enough water is added to meet infiltration needs because the infiltration rate usually changes during irrigation. As a result of these practical factors, irrigation runs are usually longer and furrow stream sizes are larger than needed, and erosion results, particularly at the heads of the furrows.

Characteristics of flow and silt load along irrigation furrows in two closely controlled tests were reported by Smith and Mech (1967) (Table 1). The flow was carefully controlled into each furrow and the runoff and sediment loss was measured from the upper, middle and lower third of each furrow. The run length was 274 m and the slope was 2 per cent. The flow into each furrow was about 15 per cent greater in test 2 than in test 1. Results of these studies clearly illustrate that erosion was greatest where stream size was largest. Soil eroded from the upper third was deposited in the middle and lower thirds as the stream size, and thereby the energy to erode and the capacity to transport sediment, decreased because of infiltration. Results from these studies contrast to erosion resulting from rainfall which is usually more severe down slope where stream sizes are large enough to erode and where slopes are greatest.

The common practice on many furrow irrigated farms today is to place a large enough stream in each furrow so that the water reaches the lower end of the furrow in about 2 or 3 hours for a 12- or 24-hour set. This usually allows sufficient infiltration time to replenish water depleted by the crop without reducing the stream size or requiring labor during the set. With this practice, stream sizes are often large and 40 to 60 per cent of the applied water becomes runoff, and erosion is extensive.

Another serious erosion problem is associated with the common practice in some irrigated areas of keeping the drain ditch at the lower end of the field 10 to 20 cm deeper than the furrows and at a slope steep enough that the tailwater flows rapidly away. With this practice, the ends of the furrows erode rapidly, even with very small streams. This erosion moves up the slope because erosion increases the effective slope near the end of the furrows. As the process continues, the slope is increased on the lower 5 to 10 m of the field, making it difficult to control erosion and soil loss from this portion of the field, and to achieve adequate intake because of smaller wetted perimeters. The lower ends of fields may have to be reshaped every few years because of this practice. This type of erosion is easily controlled by proper tailwater management.

Many fields with steep slopes are irrigated, and usually in the direction of the steepest slope, even though it has been recognized for decades that serious erosion results from such practices. Isrealson, et at. (1946) demonstrated over 30 years ago that increasing the slope from 1.15 to 6.07 per cent increased the erosion 16 times. About that same time, Gardner, et al. (1946) and Gardner and Lauritzen (1946) presented relationships among furrow slope, stream size and erosion. Unfortunately, irrigation farmers gave little attention to these results.

Following the early work in Utah, the USDA-SCS Division of Irrigation conducted many tests throughout the western U. S. and developed the relationship:

Max. Non-Erosive Stream Size,

$$\text{l/sec} = \frac{0.63}{\text{Slope, \%}} \qquad (1)$$

Evans and Jensen (1952) and Mech (1949) studied the effects of stream size, slope, and soil surface conditions on erosion. All of the work to date suggests that erosion may be expected on most row-cropped soils when slopes exceed 1 per cent. Erosion may be controlled reasonably well on slopes up to 2 per cent if the stream size is carefully controlled.

Public Law 92-500 has increased the interest among farmers and irrigation districts to control erosion and sediment in surface return flows. Many questions raised about erosion and sediment loss indicate that few irrigators and other personnel associated with irrigation have a good concept for visual determination of erosion in furrows. Carter and Bondurant (1976) presented a simple equation to estimate soil erosion:

$$\text{Soil erosion, } \frac{t}{ha} = \frac{1.2 \text{ x eroded area, cm}^2}{\text{furrow spacing, m}} \qquad (2)$$

Equation (2) assumes a soil bulk density of 1.2 g/cm^3 or t/m^3. They also presented a nomogram for estimating erosion losses in English or metric units.

Sediment in Surface Irrigation Return Flows

Sediment concentrations in surface irrigation return flows vary widely. Brown, et al. (1974) reported concentrations ranging from 20 to 15,000 ppm from studies of two large irrigated tracts in southern Idaho (Table 2). Sediment concentration in the canal waters are given for comparison. The sediment concentrations in most surface drains exceed those in the irrigation water several fold. an exception is the W drain, which functions as a sediment retention basin with a long retention time. The sediment loss from a field or an irrigation tract is determined by the volume of surface runoff and the sediment concentration. Brown, et al. (1974) reported a net sediment inflow for the 65,350-ha Northside tract and a net sediment outflow for the 80,030-ha Twin Falls tract. There was erosion on both tracts, but most of the sediment settled in drains on the Northside tract, whereas, much of the sediment reaching drains on the Twin Falls tract was carried to the river because flow velocities in the drains were greater and sediments did not settle and deposit in the drains.

Nutrients in Surface Irrigation Return Flows

Nutrients in surface irrigation return flows are in dissolved forms, or they are attached to sediments eroded from the land. Bondurant (1971) showed mathematically that little soluble nutrient pickup could be expected to result from nutrient diffusion out of the soil into water passing over the soil surface, and he presented field data to verify his contention. Carter, et al. (1971) found that soluble nutrient and salt concentrations in surface irrigation return flows were essentially the same as those in the applied irrigation water. Edwards, et al. (1972) stated that once nitrate enters the soil surface, it does not re-enter surface runoff. Fitzsimmons, et al. (1972), Naylor and Busch (1973) and Carlile)1972) reported that nitrate and ammonium nitrogen concentrations were about the same in surface runoff as in the irrigation water. Naylor, et al. (1972) illustrated that nitrogen concentrations in surface irrigation return flows from fields can be markedly increased when liquid nitrogen is added to the irrigation water for fertilizing the crop. Fertilizer losses in the surface runoff from this practice were proportional to the fraction of the applied water that became surface runoff during the fertilizer application. In these studies, the soluble nitrogen was added directly to the water, increasing the soluble nitrogen concentration in the irrigation water. The concentration did not change as the water passed over the soil surface.

Phosphorus is tightly held by soil, and essentially all phosphorus in surface irrigation return flow is associated with sediment. Carter, et al. (1974) and Carter, et al. (1976) have extensively studied phosphorus-sediment relationships in irrigation return flows, and their results show that total phosphorus and sediment concentrations in surface runoff are closely related, but that no such relationship exists between soluble orthophosphate and sediment concentrations. They developed a regression equation relating total phosphorus concentration to sediment concentration over a wide range of conditions. Fitzsimmons, et al. (1972) and Naylor and Busch (1973) attributed greater total phosphorus concentrations in surface irrigation return flow than in irrigation water to the greater sediment concentration in the runoff water. Data reported by Carlile (1972) also illustrate the close relationship between sediment and total phosphorus concentration.

Results from many investigations show conclusively that increases in nutrient concentrations from the irrigation to the surface runoff water are closely associated to erosion and subsequent increase in the sediment concentration in the surface runoff water. Therefore, controlling the sediment in surface irrigation return flows will also control most of the nutrients.

Biocides in Surface Irrigation Return Flows

There is little published information on biocide concentrations in surface irrigation return flows. There is considerable information available on biocide concentrations in surface runoff from nonirrigated lands. A review of the literature indicates that except where biocides are applied to the water, or where they are washed off plant material in soluble forms by rain or by sprinkle irrigation, the biocides in surface runoff water are adsorbed to sediments (Evans and Duseja, 1973). Unpublished data from analyses of surface drainage waters and sediments from the Northside and Twin Falls tracts show that essentially all of the biocides are adsorbed to sediments (Carter, 1975). The available information indicates that controlling sediments in surface irrigation return flows will also control most of the biocides.

Controlling Sediments and Associated Nutrients and Biocides in Surface Irrigation Return Flows

There are three broad general ways to control sediments and associated nutrients and biocides in surface irrigation return flows. One is to eliminate or reduce surface irrigation return flow. The second is to reduce or eliminate soil erosion so that there will be little or no sediment in surface runoff from irrigation. The third is to remove sediments and associated materials from surface irrigation runoff before these waters enter natural streams. If runoff can be eliminated, obviously there would be no need for the second and third general ways of control. Any farmer or irrigation district making sufficient progress on the first two ways, so that sediment and associated material concentrations are reduced below problem levels, will no longer need to consider the third way. Such progress should be the aim of irrigated agriculture, with the recognition that many years may be required to achieve this goal. However, much immediate progress could be made if presently available technology were applied (Carter, 1972).

Eliminating or Reducing Surface Irrigation Return Flows

There are irrigation methods that produce no surface runoff. These include properly designed and operated sprinkle sytstems, basin, trickle, some border irrigation and level furrow systems. These methods all have limitations. Basin, border and level furrow methods are limited to nearly level land. Capital investment is high for center pivot, side roll and solid set sprinkle systems and even higher for trickle systems. Furthermore, energy requirements for sprinkle system operation are high and energy is limited. Batty, et al. (1975) compared energy inputs involved in the installation and operation of various sprinkle and surface irrigation systems and found that on a total annual energy basis, surface systems required only 10 to 22 per cent as much energy as sprinkle or trickle systems where some pumping was required for surface systems (Table 3). Energy requirements for gravity surface systems would be less than for those requiring pumping energy.

Sprinkle irrigation is an efficient means of applying water and can be used on lands too steep for surface irrigation and lands with undulating topography. The land area under sprinkle irrigation is rapidly increasing, but energy restraints may limit development in some areas. Certainly, utilizing sprinkler systems where practical can eliminate or reduce surface return flows. However, larger center pivot systems apply water at high rates and may cause serious runoff problems (Pair, 1968)).

The recirculating or pump-back system described by Bondurant (1969) and others (Davis, 1964 and Pope and Barefoot, 1973) is a useful method for eliminating, or greatly reducing, surface irrigation return flows from farms. This method uses a basin or pond at the lower end of the field to catch surface runoff. A pump returns the water to the upper end of the field or to another field for reuse as irrigation water. Erosion is not eliminated and sediments deposited in the basins must be removed mechanically, but sediment is prevented from leaving farms and entering natural streams.

Carter and Bondurant (1976) have summarized and discussed irrigation methods with little or no surface runoff in more detail. They point out that eliminating or greatly reducing surface irrigation return flows may cause other problems in the irrigated West. Many farmers depend wholly or in part upon surface return flows from upstream irrigated farms or tracts for their irrigation water supply. Many surface irrigated tracts operate on a reuse principle so that the only water entering streams is surface runoff from the farms at lowest elevation in these tracts.

Eliminating or greatly reducing surface runoff is a means to control sediments and associated materials in surface irrigation return flows in some areas, but changing to irrigation practices with no runoff would, in many instances, cause other problems and require costly changes in system design and operation. Where changes are practical, they should be implemented.

Reducing or Eliminating Erosion

Controlling Slope

Land slope greatly influences erosion. Results of many investigations have shown that erosion may be expected on most row cropped soils where slopes are 1 per cent or more (Mech, 1959; Mech and Smith, 1967; Swanson, 1960; Swanson and Dedrick, 1967; Harris and Watson, 1971). Erosion may be controlled reasonably well up to slopes of 2 per cent, but fields with slopes greater than 2 per cent should be examined carefully to see if they can be irrigated by different methods. Changing the direction of irrigation to one of lower slope, contour irrigation and land grading to reduce the slope near the lower ends of the fields to decrease flow velocity are possible ways of controlling slope. These changes are not without problems. Farmers resist contour farming because usually short rows result, thereby adding difficulty to farming operations with large equipment.Grading to decrease the slope and flow velocity usually causes furrows to fill with sediment and flooding or lateral flow between furrows results. Nevertheless, where slopes can be reduced to 1 per cent or less, the amount of erosion and sediment loss can be reduced.

Controlling the Furrow Stream Size

Excessive stream sizes cause serious erosion on sloping land (Mech, 1959; Mech and Smith, 1967). Devices that positively control the amount of water from the pipeline, flume or ditch into each furrow are essential to effective erosion control and efficient irrigation. Most valves, gates, siphon tubes, and other flow control devices permit small flow adjustments that remain unchanged until reset. This equipment is available, but is often not used or used incorrectly.

A greater initial flow is often desired to get the water to the end of the furrow and allow a uniform intake time. Once the water reaches the end, the flow should be reduced or cutback to decrease erosion and runoff. However, when the stream size is reduced for a given water set, the excess water from the set after cutback must be used elsewhere or wasted in most systems with open ditches. Applying it to other sections of the farm would require that irrigation sets be made several times each day, and this conflicts with other farming operations. Humpherys (1971) developed several systems for reducing flows in furrows after water has reached the ends. One system splits the set, applying all the water alternately to half the set until water reaches the ends of the furrows, then applies the water to the entire set so that flow in each furrow is one half the amount initially.

Much can be done with present technology to reduce erosion by controlling stream size. Further development and application of automated systems with proper stream size control would bring about a marked reduction in erosion and sediment loss from furrow irrigated land.

The Run Length

The run length and furrow stream size are closed related. Short runs can be irrigated with small streams with very little erosion and sediment loss, but cross ditches interfere with farming practices. The multiset systems developed by Rasmussen, et al. (1973) provide an alternative to cross ditches for shortening the run length. Aluminum or plastic pipe distributes water at several points along the furrows so that small streams are used and erosion and runoff is essentially eliminated. Pipes are moved for tillage, seeding and harvesting operations.

Worstell (1975) field tested an adaptation of the multi-set systems with buried laterals so farming operations could be carried out without moving pipe. The system is fully automated and can be programmed to apply water daily according to ET depletion, or less often if desired. Initial results are promising, but further testing is needed. These kinds of systems have great potential for controlling stream size or length of run. With such systems, erosion and sediment loss can be essentially eliminated and irrigation efficiency can be greatly increased.

Controlling Irrigation Frequency and Duration

Erosion and sediment loss are highest during the early part of an irrigation after soils have been disturbed by cultivation. Mech (1959) reported a soil loss of 39.9 t / ha from a recently cultivated corn field during the first 32 minutes runoff. The total soil loss for a 24-hour irrigation was 50.9 t / ha, and it occurred during the first 4 hours even though runoff increased after that because of decreasing intake. Less erosion would occur with less frequent irrigations, particularly when irrigations follow cultivations.

Alternate furrow irrigation is another practice to reduce erosion. Only half as much soil surface is contacted by water and erosion is less. However, the success of alternate furrow irrigation depends upon soil conditions. Some soils do not permit adequate lateral water movement, or deep percolation losses may be too great during the increased time required for lateral movement.

Removing Sediment and Associated Nutrients and Biocides From Surface Irrigation Return Flows

Controlling tailwater

The most important factor in controlling tailwater is to limit the amount of runoff. The smallest stream that will irrigate to the end of the furrow will add nearly as much water to the soil as a larger stream, and the amount of runoff water will be much less and more easily controlled. Practices that will assure more uniform intake rates of individual furrows need to be developed and utilized for better runoff control.

The drain ditch at the lower end of the field should be shallow and at a low slope, or checked so that water moves slowly and sediments settle out before the water leaves the field. Checking the drain ditch forms miniature sediment basins. Brockway, et al. (1976) found that mini-basins receiving runoff from a few furrows each, effectively controlled sediment losses.

Passing tailwater through grass or other close growing crops efficiently filters sediments from water. Grass buffer strips, heavy seeded fall grain strips, or alfalfa at the ends of row cropped fields, can greatly reduce sediment losses. Another alternative is to utilize runoff from row crops to irrigate alfalfa, pasture or other close growing crops.

Utilizing Sediment Retention Basins

Much of the sediment in surface irrigation return flows can be removed in sediment retention basins. The need to remove sediments from surface irrigation return flow will continue for many years even though much can be done to reduce erosion and sediment loss from irrigated fields. Basins are a partial cure to the sediment problem, not a prevention. Their construction and periodic cleaning are relatively expensive.

The effectiveness of simple sediment retention basins is illustrated by a 0.45-ha basin removing 2390 t of sediment during two irrigation seasons from part of the runoff water from a 117-ha tract. The erosion loss was 20.5 t/ha. The sediment removal efficiency exceeded 80 per cent when the sediment concentration exceeded 0.1 per cent and it was never less than 65 per cent (Robbins and Carter, 1975).

The trapping efficiency of sediment basins is directly related to the forward velocity, settling depth and particle size of the sediment. Basins can be designed to remove given particle sizes if the flow volume is known so that velocity relationships can be established. The trapping efficiency of one district basin designed to remove at least 50 per cent of the incoming sediment has not been less than 65 per cent over 5 years (Brown, 1977). More information on design criteria is needed and some is being developed and tested currently (Bondurant, et al. 1976).

Particle size segregation takes place as sediments settle in basins. Sediments remaining in suspension are mostly in the clay size fraction, although much clay settles in aggregates because dispersion is not complete. Dispersion is greater in waters with very low salt concentration, and more clay remains suspended. The clay size fraction is richer in phosphorus, so passing surface runoff through a sediment retention basin can give an apparent phosphorus enrichment when phosphorus is measured per unit of suspended material. However, sediment retention basins conserve phosphorus because most of the sediment is removed by the basins (Carter, et al. 1974).

The use of sediment retention basins can be discontinued for any field, farm or district where implementation of erosion control practices have eliminated excessive sediment concentrations in the surface irrigation return flow. Also, use of basins may not be needed every season, depending upon the crops grown. Non use during one or more seasons when close growing crops are grown would allow the collected sediment to dry and time for cleaning.

CONCLUSIONS

The quantity of sediment and associated nutrients and biocides in surface irrigation return flows could be reduced significantly by applying presently available control technology. There are restraints to direct application of some practices such as the energy limitation for converting to sprinkle irrigation, and the dependence of some farmers on the surface runoff from upstream farms or tracts for their supply or irrigation water. The development of irrigation methods with precise flow controls that distribute water over the entire field with little or no runoff and with low energy requirements should receive top priority. The buried lateral multiset system is an example of systems that might be developed and improved. The basic relationships among stream size, flow velocity, erosion, sedimentation, run length and

TABLE 1

Water Flow and Soil Loss along Irrigation Furrows (Mech and Smith, 1967).

Distance from upper end		*Flow per furrow per minute*		*Soil loss per furrow*		*Runoff*	*Travel Time*	
							From point of application	*For 91-m (300-ft) distance*
m	ft	liters	gal	kg	lb	%	min	min
				Test no. 1				
0	0	26.6	7.03	0	0		0	
91	300	17.0	4.49	43.3	116	61	48	48
183	600	7.3	1.94	4.8	13	21	211	163
274	900	2.5	0.67	0.4	1	2	682	471
				Test no. 2				
0	0	30.6	8.08	0	0		0	
91	300	20.7	5.46	51.1	137	66	24	24
183	600	11.9	3.14	14.2	38	35	98	74
274	900	5.4	1.42	0.7	2	8	436	338

sediment settling velocity need to be integrated into new technology that will permit modification of various control parameters. New ideas are needed, and new and better water control systems need to be developed.

TABLE 2

Sediment Concentrations in Irrigation and Drainage Waters For Two Large Tracts During the 1971 Irrigation Season.

Drain	*Sampling Date*												
	Northside Canal Company, 65,350												
	4/20	5/3	5/17	5/28	6/7	6/15	6/29	7/13	7/26	8/10	8/24	9/8	9/28
	Sediment Concentrations in parts per million												
K	240	190	270	140	200	160	110	120	90	90	90	40	40
N-32	380	100	150	120	170	90	70	30	180	20	20	60	50
J-8	1,580	1,430	2,610	510	660	660	300	80	170	110	70	100	110
S	320	350	110	140	100	200	440	110	130	90	60	130	140
W-26	160	80	100	60	100	130	100	60	160	100	40	50	50
W	160	50	60	30	30	40	20	20	30	20	20	10	40
	Twin Falls Canal Company, 82,030 ha												
				5/25	6/2	6/15	6/29	7/13	7/26	8/10	8/24	9/8	9/28
	Sediment Concentrations in parts per million												
Rock Creek	—	—	—	540	300	140	190	310	320	390	200	120	150
Cedar Draw	—	—	—	200	210	100	120	220	550	520	330	150	200
Filer Drain	—	—	—	710	400	210	710	2,250	2,120	110	820	270	290
Mud Creek	—	—	—	260	180	140	130	120	200	190	250	260	130
Deep Creek	—	—	—	200	110	70	80	60	70	110	10	100	90
			4/20	5/14	5/26	6/23	7/6	7/20	8/3	8/17	9/2	9/16	10/5
Hansen Drain	—	—	—	1,550	380	510	3,180	14,500	4,970	290	3,160	280	—
Kimberly Drain	—	—	4,180	1,080	360	610	2,860	1,420	4,960	180	150	70	40

Canal Water, Monthly Average Concentrations

	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
Northside	63	63	29	37	33	26	26	26	—
Twin Falls	74	40	52	85	55	29	29	29	29

TABLE 3

Total Annual Energy Inputs, in Thousands of Kilocalories (or Gallons of Diesel Fuel) Per Acre Irrigated for Nine Irrigation Systems, Based on 36-in. (915-mm) Net Irrigation Requirement and Zero Pumping Lift (Batty, et al., 1975).

Irrigation system	*Installation energy*[a]	*Pumping energy*	*Installation per pumping energy ratio*	*Labor energy*	*Total energy*
Surface without Irrigated Runoff Recovery System	103.2	35.2	2.93	0.50	138.9 (15.0)
Surface with Irrigated Runoff Recovery System	179.9	48.0	3.75	0.30	228.2 (24.6)
Solid-set sprinkle	614.1	770.0	0.80	0.40	1,384.0 (149.5)
Permanent sprinkle	493.6	770.0	0.64	0.10	1,263.7 (136.5)
Hand-moved sprinkle	159.7	804.0	0.20	4.80	968.5 (104.6)
Side-roll sprinkle	200.3	804.0	0.25	2.40	1,007.1 (108.8)
Center-pivot sprinkle	388.5	864.0	0.45	0.10	1,252.6 (135.3)
Traveler sprinkle	288.9	1,569.0	0.18	0.40	1,858.0 (200.7)
Trickle	530.5	468.0	1.13	0.10	998.6 (107.8)

[a] These figures were obtained by dividing the installation energy by the system life and by the net acres irrigated and multiplying by 1.03 to include annual maintenance energy for all systems except for solid set where 1.01 was used.

Conversion factors: 1 kcal = 4.19 kJ; 1 kcal = 0.000108 gal of diesel.

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Quality of Irrigation Return Flow From Flooded Rice Paddies

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ABSTRACT

A three year field and laboratory study was conducted to determine the quantity and quality of irrigation return flow from flooded rice culture. Both intermittent and continuous flow irrigation techniques were evaluated. Selected pesticides and nutrients were applied at recommended and excessive rates. The concentrations of nitrate, phosphate and potassium in the return flow were all within levels acceptable for drinking water. Only small amounts of the fertilizer applied to the soil before flood or in the floodwater were lost in the irrigation return flow. The large amounts of rainfall received each year diluted the salts in the floodwater so that the salt load of the irrigation return flow did not differ greatly from that of the irrigation water. Increases in the electrical conductivity of the floodwater resulted from the release of certain ions from the soil after fertilizer applications. These increases lasted for periods of 5-10 days.

The 96 hour median tolerance level of catfish to three of the four pesticides tested were lower in the water from the paddies than for tap water. Excessive rates of the pesticides resulted in concentrations in the paddy water which were greater than the 96 hour TLM concentration. For the recommended rates, the concentrations of propanil exceeded 10% of the 96 hour TLM until 24 hours after application. For Molinate 10% of the TLM was not exceeded at any time, for carbofuran the period was 20 days, while for carbaryl the period was 6 days. It is suggested that water should not be released from the fields during the specified periods after application. Evidence was found that some of the pesticides which remain on the foliage are later washed into the flood water by rain, thus increasing the concentration in the return flow rather than decreasing them by dilutions. Only low concentrations of the toxic metabolites of the pesticides were found in the field.

INTRODUCTION

As technology advanced, particularly the methodology and instrumentation, the distribution and levels of hazardous chemicals in our environment are revealed. The simplest and most expedient solution to eliminate hazardous materials would be to ban the use of all potential pollutants. This would include virtually all soil amendments and chemicals employed in agricultural production.

We have reached a point where the fertility status of many of our soils is dependent upon "bagged" inputs. We have mutated the hardiest of insects, such that natural control is virtually impossible. More succinctly stated, many of the chemicals deemed pollutants are presently essential if we are to maintain our current socioeconomic standard of living.

The most logical approach is to determine the longevity and mobility of the chemicals used for agricultural production and to select those chemicals and management practices which minimize pollution hazards.

Rice is presently an important cash crop in Arkansas, Louisiana, Texas and California with approximately 2.3 million acres of irrigated rice grown yearly. Fertilizer amendments and pesticides are essential for continued production at economically feasible levels. However, fresh water supplies for urban use and the estuaries along the coastal regions are relatively unbuffered geographically from the rice growing areas.

The primary objective of this project was to assess the pollution potential of irrigation return flow from flooded rice cultivation with respect to fertilizer elements and pesticides.

EXPERIMENTAL DESIGN

Field studies were conducted for three years on a group of 12 small rice paddies. Earthen levees were constructed along the boundaries of the plots and plastic barriers interred to a depth of 90 cm within the dikes to retard water from moving horizontally between plots. Flooded surface area of the plots averaged 300 m^2.

Two irrigation schemes, continuous flow and a more static intermittent flow system, were evaluated. A water balance was ascertained for each plot based on the quantity and frequency of irrigation, precipitation, evaporation, transpiration, runoff, and leachate through the soil profile. A system of weirs and reservoirs was installed to manage water levels in accordance with the irrigation schemes tested (Figure 1). Water stage recorders continuously monitored water levels in each plot. Intermittent irrigation was managed by metering water into the plots as needed to maintain a flood of between 4 and 10 cm. Continuous flow plots were provided with an outflow at 10 cm above the soil surface. An equivalent of 0.9 cm of water for the entire plot was metered in each day.

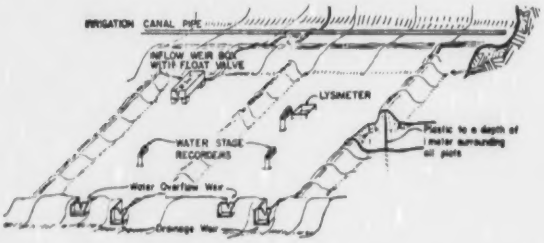
IRRIGATION CANAL PIPE
INFLOW WEIR BOX WITH FLOAT VALVE
LYSIMETER
WATER STAGE RECORDERS
Plastic to a depth of 1 meter surrounding all plots
Water Overflow Weir
Drainage Weir

Figure 1. Schematic diagram of two of the research plots showing water control devices.

Several methods were used to measure the movement of water into the profile. Infiltration under flooded paddy conditions was determined by comparing lysimeter data and water loss from plots. Infiltration was also estimated on small plots isolated with metal frames and surrounded by water.

TABLE 1

Rate of fertilizers and pesticides applied given in kg/ha active ingredients.

	Recommended	*Excessive*
Nitrogen as N	134.4	179.2
Phosphate as P_2O_5	44.8	112.0
Potassium as K_2O	22.40	89.60
Propanil	3.36	6.72
Molinate	3.36	11.20
Carbofuran	0.56	3.36
Carbaryl	1.12	5.60

Plots were randomized with respect to application rates of nutrients and pesticides. Excessive rates of both were applied to the same plots. Rates employed for the pesticides and fertilizers are given in Table 1. Fertilizers and pesticides were applied to rice plots in a fashion which was as similar to normal cultural practices as possible.

Flood water in plots were sampled on a schedule designed to provide detailed information following events such as irrigation, heavy rainfall, and applications. In addition, the irrigation water was sampled at the canal source for comparison. Water samples for pesticide analyses were taken as soon after application as possible and assigned a relative time of zero hours. Subsequent samples were generally taken 24, 48, 96, 192, 384, and 768 hours. Time zero for propanil was approximately 24 hours following the application since that was when the plots were flooded. Plots were already under permanent flood when the other chemicals were applied.

The original plan was to sample the solution of the soil profile through porous filters at 5, 15.4, 30, and 61 cm depths. However, this approach to sampling was not reliable because very little or no water could be withdrawn by suction from the tight, fine-textured, very slowly permeable soil. Thus, the lack of sample, sample volume, and excessive variation within replication called for another sampling method.

A dialysis tube method of sample collection was used. Dialysis tubing was filled with distilled-deionized water, placed in the plots and covered with 1 cm of soil. After 24 hours of contact with the soil solution, the dialysis bags were removed and analyzed to estimate the ionic constituency of the soil solution.

Soil profile samples were taken at the beginning of the experiment to establish the background ionic constituency. Originally, the depths sampled were 0 - 15, 15 - 30, 30 - 45, 45 - 60, 60 - 76, and 76 - 91 cm in each plot. During 1974 and 1975 sampling was restricted to the surface and the 0 - 15 cm depth since it became evident that water percolation was very slow and the first 15 cm of the profile was most important.

Fish bioassays were employed to aid in evaluating the water quality of the paddy water released at the end of the field experiment.

RESULTS AND DISCUSSION

Water Balance

The water balance of a rice paddy over a season may be written as:

$$P + I = EV + TS + R + L$$

where P is the amount of precipitation, I is the depth of irrigation, EV is the evaporation, TS is the transpiration, R is the runoff, and L is the percolation loss. The left side of the equation summarizes the gains and the right side the losses. The water balance subdivided into gains and losses during the period of permanent flood for 1974 and 1975 for both irrigation treatments is given in Table 2.

TABLE 2

Water balance during the period of permanent flood for1974 and 1975 for both irrigation treatments.

	Intermittent Irrigation		*Continuous Irrigation*	
Gains	74	75	74	75
Rainfall	27.6	48.4	27.6	48.4
Irrigation	43.6	24.7	90.0	77.9
Total	71.2	73.1	117.6	126.3
Losses				
Runoff	26.2	31.2	34.3	73.7
% of total app.	36.8	42.6	29.2	58.3
Leachate	12.4	12.0	12.4	12.0
% of total app.	17.3	16.4	10.5	9.5
EVTS	45.6	39.6	45.8	39.6
% of total app.	64.0	54.0	38.9	31.4
Total	84.0	82.9	92.5	125.3
% of total app.	118.1	113.1	78.6	99.2

Input from precipitation was greater in 1975 than in 1974. Total input was approximately the same in the intermittent irrigated plots, but was a little higher in the continuous flow plots. However, the difference generally reflects the increased depth employed in the continuous management scheme in 1975.

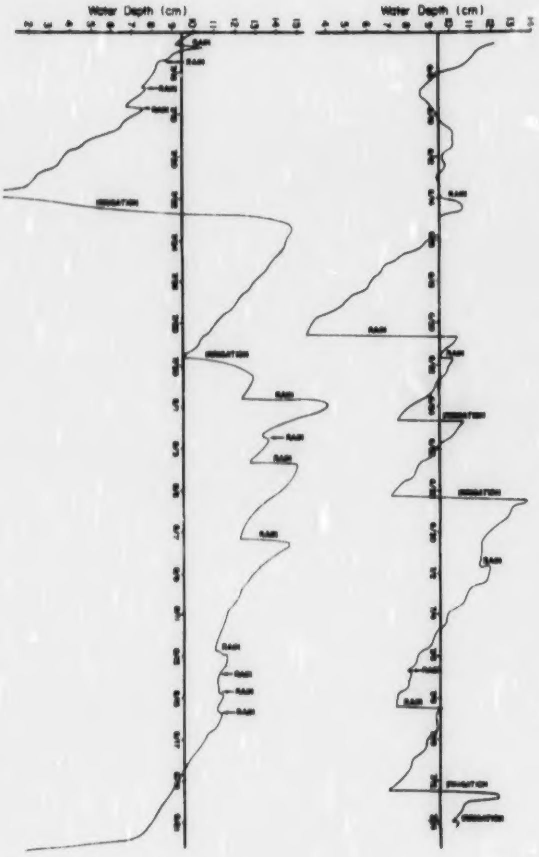

Figure 2. Seasonal patterns of water depth in intermittently irrigated plots during 1974. The date line represents the bottom of the 10° outflow weir.

The increased runoff in 1975 was due mainly to the storm events. Runoff is reflected in the seasonal patterns of water depth with time relative to the 10° outflow weir in Figures 2 and 3 for 1974 and in Figures 4 and 5 for 1975.

The water which moved into the soil profile which was not used up by the plants was considered to be leachate. It amounted to about 12 cm each year, however piezometer data shows that the wetting front never penetrated past 60 cm; thus, movement through the soil was very slow.

Under both management practices, far more water was applied to the field than would have been needed to supply the evapotranspiration. With the continuous flow management system, the water applied by irrigation was 2 1/2 times that needed to satisfy the evapotranspiration and was over 3 times

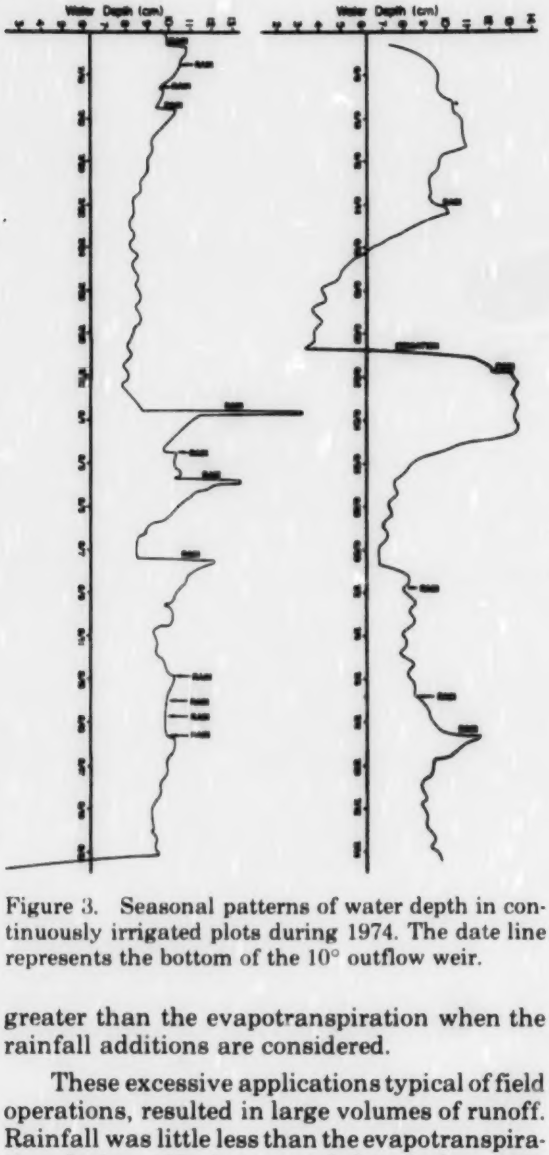

Figure 3. Seasonal patterns of water depth in continuously irrigated plots during 1974. The date line represents the bottom of the 10° outflow weir.

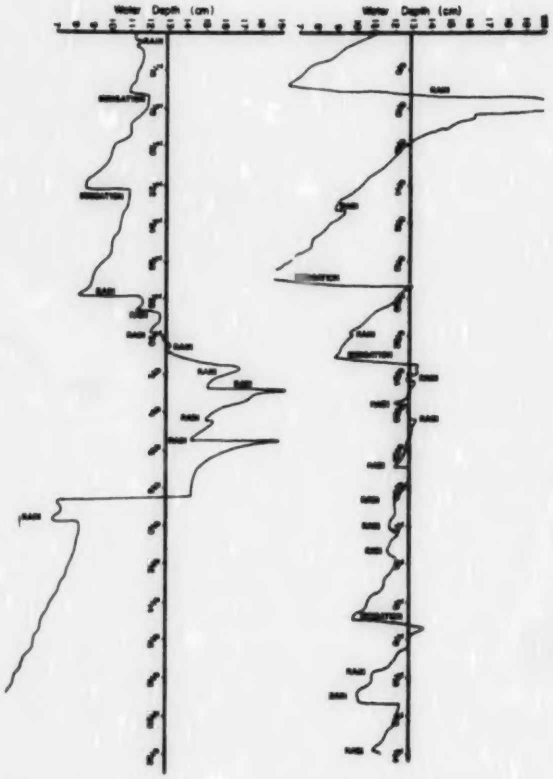

Figure 4. Seasonal patterns of water depth in intermittently irrigated plots during 1975. The date line represents the bottom of the 10° outflow weir.

greater than the evapotranspiration when the rainfall additions are considered.

These excessive applications typical of field operations, resulted in large volumes of runoff. Rainfall was little less than the evapotranspiration during 1974 but exceeded it during 1975. While these rains are scattered and do not come at exactly the time they are needed, careful management of irrigation water levels would make it possible to increase the amount of rainfall utilized and to decrease the volume of runoff.

Salt Balance

Electrical conductivity (E.C.) values of the irrigation supply and plot flood water, averaged over the respective treatments, are given in Figures 6 and 7 for intermittent and continuous flow irrigation schemes, respectively. Analyses of variance indicated that time of sample collection, fertilizer application rate, and irrigation management had highly significant effects on mean E.C. values in 1974 and 1975. Data from 1973 are too sparse to indicate significant trends due to treatments, although means did vary significantly with time.

Conductance is a measure of the current carried by electrolytes, and as one would expect the excessive fertilizer application rate resulted in higher E.C. values. E.C. values were greater under the impoundment irrigation management.

It is evident from the data that the increase in E.C. following fertilizer application was primarily a temporary effect. Fertilizer incorporation into the soil and/or applied to dry soil prior to flood resulted in lower salt levels in the plot water sampled, as evidenced by the fact that peak concentrations were about equal, although the pre-plant and tillering application rates were twice the panicle differentiation rate (Table 3).

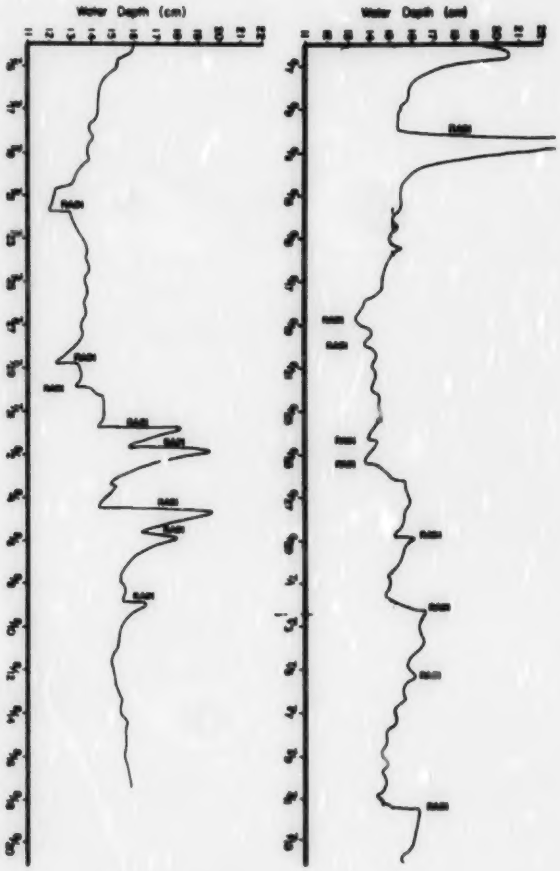

Figure 5. Seasonal patterns of water depth in continuously irrigated plots during 1975. The date line represents the bottom of the 10° outflow weir.

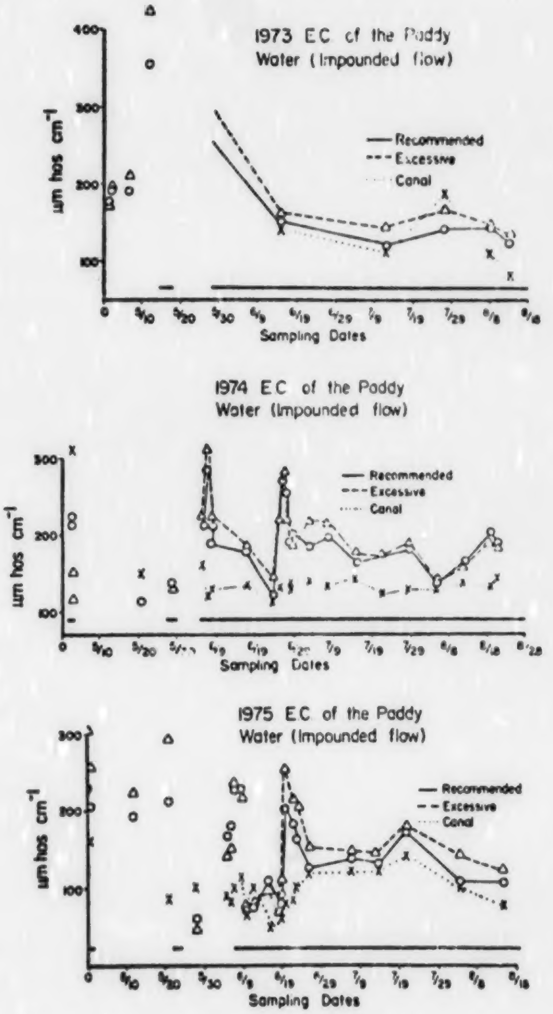

Figure 6. Electrical conductivity in µmhos/cm for water in impounded plots and in the canal.

Irrigation and paddy water pH values for continuous flow and intermittent irrigation management schemes are given in Figures 8 and 9. The general trend was for the pH of the paddy to increase toward that of the irrigation water with time. Significant decreases in pH correspond to the $(NH_4)_2SO_4$ applications. One could expect this since $(NH_4)_2SO_4$ is an acidic salt. While the excessive application rate resulted in generally lower pH values, analyses of variance indicated that rate was not significant at a 5% level in either 1974 or 1975.

The intermittent irrigation scheme resulted in a significantly lower pH in 1974, but imparted little variation on treatment means in 1975. The difference between the two years may be due to the fact that a smaller percentage of the total water volume was exchanged under the continuous flow management scheme in 1975. Continuous flow plots had been made deeper in 1975 to investigate the influence of plot depth. Thus, the deeper plots resulted in a larger total water volume, lessening the impact from 0.9 cm/day outflow.

The salt load of each irrigation and all runoff was calculated from plot water concentrations and the water balance data for both continuous and intermittent irrigation treatments (Table 4). More salt was applied to the intermittent flow plots during 1974 than in 1975, but the greater concentration of salts in the runoff during 1974 resulted in more salt being removed. Continuous flow plots received much more water than intermittent irrigated plots, consequently, the amount of salt added to the plots was greater. However, that lost to runoff was far less than the applied indicating that even under the continuous flow system, the plots were absorbing much of the input from the fertilizer applications and load of the irrigation supply.

Nutrients

The concentrations of nitrates, ammonia, phosphates, potassium, and the associated cations and ions were monitored in the floodwater throughout all seasons. For the continuous irrigation plots, through which water was flowing at all times, the data collected is representative of the outflow water.

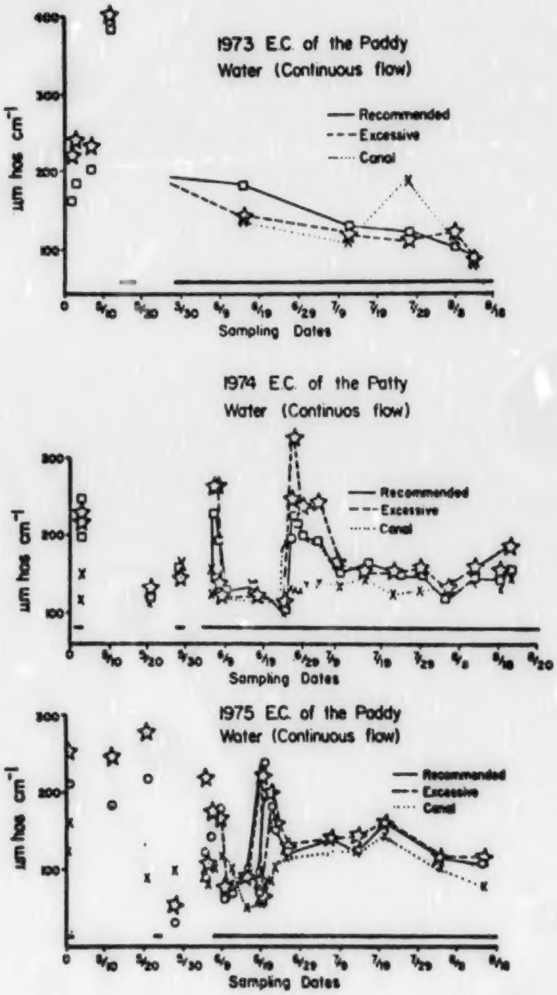

Figure 7. Electrical conductivity in µmhos/cm for water in continuous flow plots and in the canal.

TABLE 3

Associated ions added with fertilizers during the three years.

Growth stage of rice	*Fertilizer element*	*Associated anion/cation*	*Associated ion added*	
			Recommended rate	*Excessive rate*
Preplant	NH_4^+	SO_4^{--}	184	246
	K^+	Cl^-	16	64
	H_2PO_4	Ca^+	13	33
		SO_4^{--}	3	7
Preflood	NH_4^+	SO_4^{--}	184	246
Panicle Differentiation	NH_4^+	SO_4^{--}	92	121

TABLE 4

Salt balance during the rice growing season during 1974 and 1975.

Year	*Irrigation technique*	*Salt applied in Irrigation water*	*Salt lost in runoff*	*Salt gained by flood*
		kg/ha	kg/ha	kg/ha
1974	Impounded	528	559	-31
1974	Continuous	993	575	417
1975	Impounded	428	433	-5
1975	Continuous	712	587.9	124

For the intermittent plots, the data represents the concentration in the outflow when it occurred due to excess rainfall and, in addition, may be interpreted as the concentrations that would have occurred in the outflow had the water been deliberately released at any time during the season. Typical nitrate concentrations in the impounded treatment are shown in Figure 10. The highest concentrations are associated with the period between planting and permanent flood when nitrogen was liable to oxidize between irrigations. A small peak occurred shortly after the NH_4SO_4 surface application at the time the permanent flood was initiated, and an even smaller peak occurred as a result of the water application at panicle differentiation. All of the concentrations measured were well below the 10 ppm NO_3-N considered to be the upper limit for drinking water. Typical data on the concentration of NH_3-N are shown in Figure 11. The concentrations were low during the period when plots were not flooded despite 40% of the N being applied at seeding. Peaks which have half lives of the order of 2 to 3 days occurred after the 40% was surface applied just before flooding and again after the 20% application at panicle differentiation. Peak concentrations were typically 10 ppm NH_4-N, but occurred only on one or two days each season. By approximately five days after applications, the concentrations decreased to below those in the incoming canal water.

Concentrations of K were low and typically of the same magnitude as the canal water. The concentrations of ortho-phosphates followed similar patterns.

TABLE 5

Propanil recovered in water from treated rice plots sampled 0 and 24 hours following the flood in 1973.

Treatments		*Hours following flood*	
Water mgt.	*kg/ha propanil*	*0*	*24*
		kg/ha†	
Impounded	3.4	1.608	0.001
Impounded	6.8	2.210	0.001
Flowing	3.4	1.442	0.002
Flowing	6.8	2.343	0.002
Experiment Ave*† SNK (p=2), 0.692		1.901_a	0.002_b

†Values represent mean of 3 replications.

*†Averages over entire experiment not followed by the same letter are significantly different at the 5% level using a Student-Newman-Keul's range test.

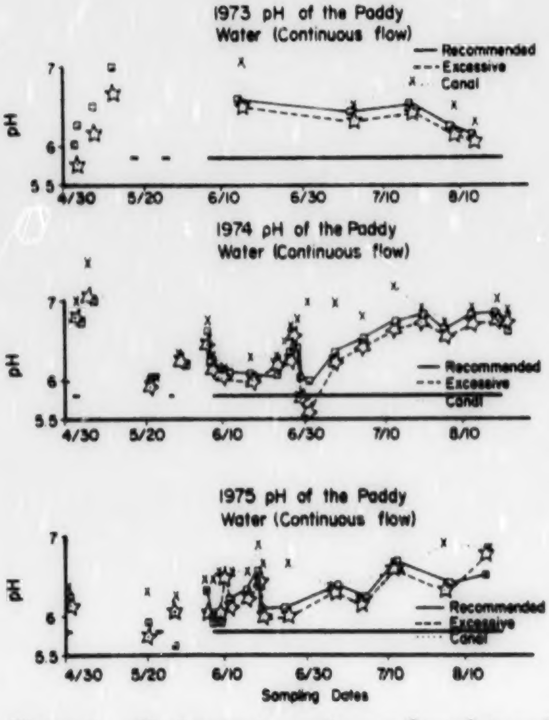

Figure 8. pH of water in continuous flow plots and in the canal.

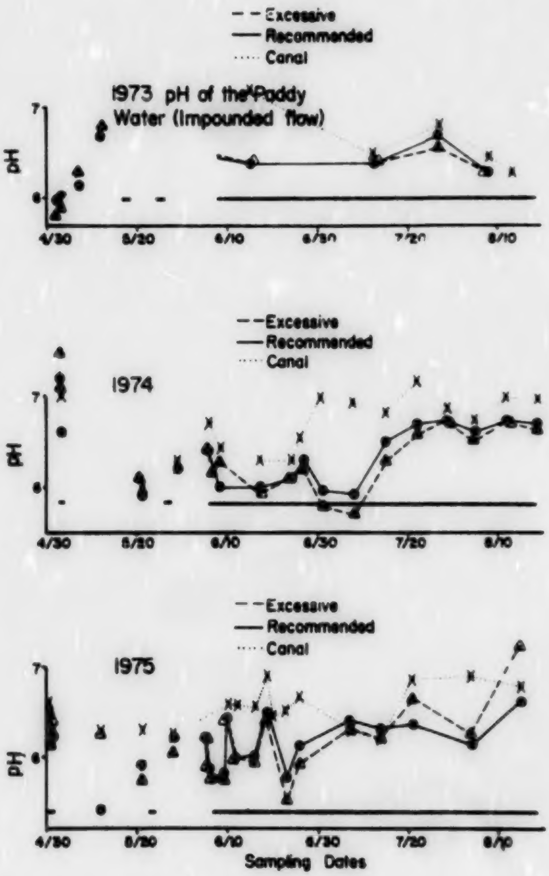

Figure 9. pH of water in impounded plots and in the canal.

Pesticides

The pesticides employed in this study were propanil (3', 4' — dichlo-ropropionanilide), molinate (S-ethyl-hexahydro-1-H-azepine-1-carbothioate), carbofuran (2, 3-dihydro-2, 2-dimethyl-7-benzofuranyl-N-methyl carbamate), and carbaryl (1-naphthyl-N-methyl carbamate).

Propanil was applied as a foliar spray 24 hours prior to the permanent flood application. The 1973 experiment indicated that propanil dissipated from the flood water within 24 hours (Table 5). A more rigorous sampling schedule was employed in 1974 and 1975 to determine the rapidity with which propanil dissipated in the plots (Tables 6 and 7). Although propanil concentration was about constant or increased over the first 12 hours, it did not persist at significant levels 24 hours following the flood application. Plot water concentrations were generally found

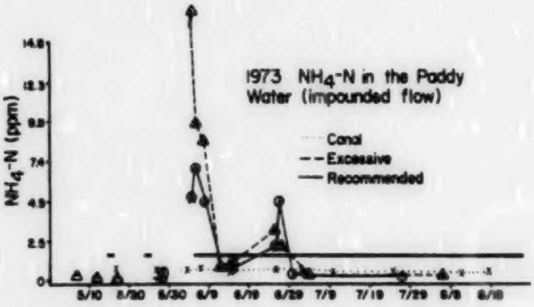

Figure 10. Concentration of NO_3-N in ppm in impounded plots and in the canal water.

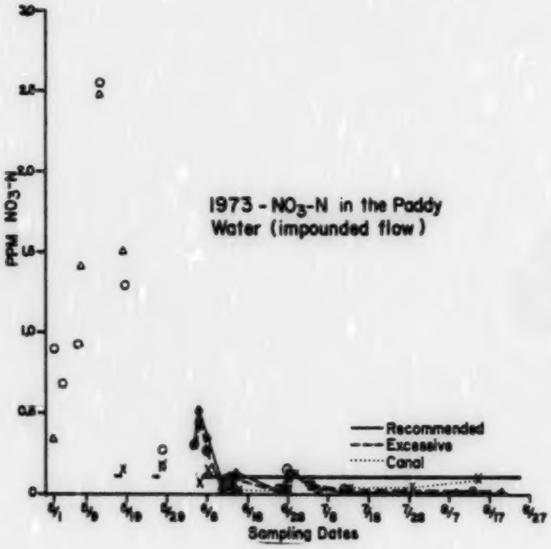

Figure 11. Concentration of NH_3 + in ppm in impounded plots and in the canal water.

to be a function of that washed from the foliage (Figures 12 and 13).

Molinate was applied in granular formulation by broadcast over the entire plot. Application followed the permanent flood by 8 days in 1973 and by 18 days in 1974 and 1975. While persistence was generally longer in the 1974 and 1975 field experiment, residue levels were more a function of application rate, and time elapsed following application (Table 8). Residues were generally greater under the intermittent irrigation management scheme all 3 years, but statistically significant only in 1973.

Molinate residual levels were found to be a logarithmic function of time (Table 9). Half-life or time required for 50% reduction in the molinate residual level was calculated for each

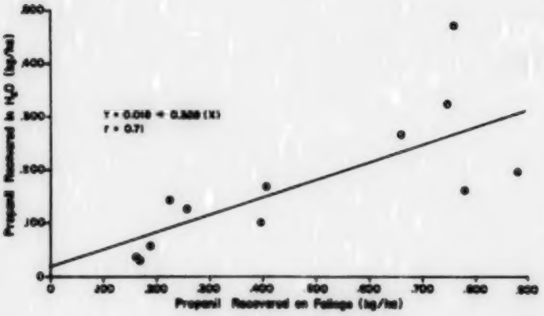

Figure 12. Propanil recovered in the water immediately following the flood as affected by the absorbed foliar concentration prior to the flood application in 1974.

replication within treatment blocks (Table 10). Although half-life values were longer in 1974 and 1975, the difference between years was not significant at the 5% level. Unlike the trend observed on persistence of molinate, the excessive application did not result in a significant increase in half-life.

TABLE 6

Propanil in water from treated rice plots sampled 0, 3, 6, 12 and 24 hours following the flood in 1974.

Treatments		*Hours following flood*				
Water mgt.	*kg/ha propanil*	*0*	*3*	*6*	*12*	*24*
				kg/ha†		
Impounded	3.4	0.136	0.070	0.041	0.167	0.008
Impounded	6.8	0.330	0.242	0.249	0.105	0.008
Flowing	3.4	0.078	0.090	0.087	0.091	0.011
Flowing	6.8	0.322	0.249	0.236	0.241	0.005
Experiment Ave*† SNK (p=5) 0.113		0.217_a	0.163_a	0.153_a	0.151_a	0.008_b

†Values represent mean of 3 Replications.

*†Averages over entire experiment not followed by the same letter are significantly different at the 5% level using a Student-Newman-Keul's range test.

Irrigation management scheme had a highly significant influence on half-life values within a given year, where intermittent flow (the more static system) resulted in a longer half-life. A first order interaction between year and irrigation management was significant at a 5% level, and suggested that the influence of intermittent flow was more pronounced in 1974 and 1975.

It was established in the laboratory, under simulated flood conditions, that molinate was dissipated biologically and apparently by aerobic organisms, since no significant degradation was noted in the sterilized controls, and molinate dissipation was greater in the more oxidized samples (Table 11). These results are consistent with those of the 3 year field experiment. Field plots were flooded 8 days prior to molinate application in 1973; wheras, the corresponding time interval was 18 days in 1974 and 1975. Thus, the longer half-life and sustained persistence in the latter two years apparently was due to a more reduced environment.

Results of the laboratory experiment in which redox potential was the only variable, clearly showed that molinate dissipation rates are affected by redox potential (Figure 14). Dissipation rates were drastically reduced at E_h values less than +72 mV.

TABLE 7

Propanil recovered in water from treated rice plots sampled 0, 3, 6, 12, and 24 hours following the flood in 1975.

Treatments		*Hours following flood*				
Water mgt.	*kg/ha propanil*	*0*	*3*	*6*	*12*	*24*
				kg/ha†		
Impounded	3.4	0.817	0.176	1.267	0.822	0.061
Impounded	6.8	1.036	1.203	1.671		0.056
Flowing	3.4	0.440	0.466	1.327	0.989	0.075
Flowing	6.8	1.108	1.036	2.525	2.306	0.208
Experiment Ave*† SNK(p=5)	0.560	0.850$_a$	0.720$_a$	1.607b	1.447b	0.100$_c$

†Values represent mean of 3 replications.

*†Averages over the entire experiment not followed by the same letter are significantly different at the 5% level using a Student-Newman-Keul's range test.

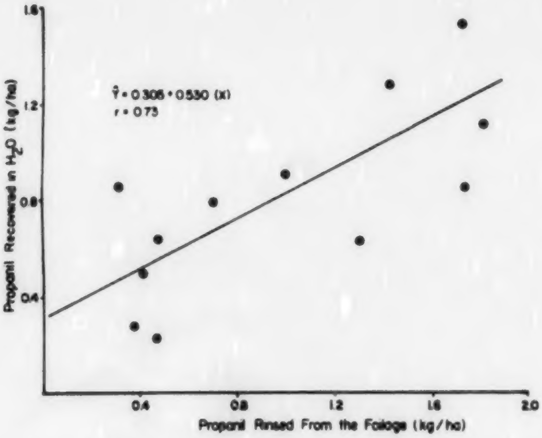

Figure 13. Propanil recovered in the water immediately following the flood as affected by the absorbed foliar concentration prior to the flood application in 1975.

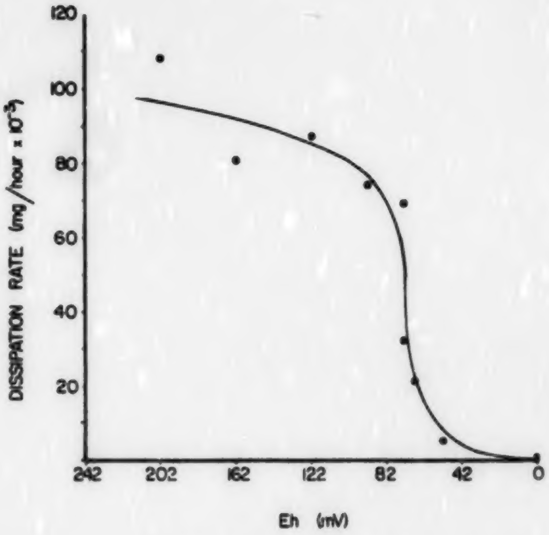

Figure 14. Molinate dissipation rates as a function of E_h.

Residual levels of carbofuran found for the various treatments with respect to time following application are plotted in Figures 15, 16, and 17 for the 1973, 1974 and 1975 experiments, respectively. Residual levels were highest initially and decreased rapidly to less than 50% of the initial concentration within 24 hours in 1973. Carbofuran residues in the water followed a different pattern in 1974 and 1975. The amounts in the water were low initially, and highest in the 24-hour samples. Carbofuran was applied in the plot water in a commercially available granular form, and sufficient time may not have elapsed for dissolution in 1974 and 1975. However, a time differential cannot explain the anomaly in the 24-hour samples. As much as 60% of that applied at the excessive rate could be accounted for in 1974, 24 hours later. Conversely only about 30% of that applied in 1973 was in the water and this maximum occurred in the zero-hour samples.

During 1973, no rain fell until after the 192-hour sampling period. This and subsequent rains had little affect on the carbofuran residual level in the flood water. During 1974, a 1.24 cm rain fell just before the 192 hour sampling period causing a second peak in concentration. Subsequent rains resulted in no increase in the

TABLE 8

Molinate recovered in water from treated rice plots in 1973, 1974 and 1975.

	Treatments		*Molinate residue (kg/ha)**						
		kg/ha	*(hours following application)*						
Year	*Water mgt.*	*Molinate*	*0*	*24*	*48*	*96*	*192*	*384*	*768*
1973	Continuous	3.4	1.133a	0.766ab	0.374bc	0.231bc	0.197bc	0.004c	0.001c
	Continuous	11.2	3.504a	2.802b	1.417c	0.572d	0.072d	0.004d	0.000
	Intermittent	3.4	1.560a	1.396a	1.157ab	0.797bc	0.251c	0.036c	0.004c
	Intermittent	11.2	6.028a	4.910b	3.659c	2.172d	0.547e	0.068e	0.005e
1974	Continuous	3.4	2.339a	2.064ab	—	1.609b	0.428c	0.021c	0.000
	Continuous	11.2	5.928a	5.225a	—	3.589b	0.967c	0.069d	0.002d
	Intermittent	3.4	1.572a	1.151a	—	0.321b	0.587b	0.061c	0.000
	Intermittent	11.2	6.908a	5.546a	—	3.762c	1.941d	0.531e	0.053e
1975	Continuous	3.4	0.007d	1.780a	1.321b	0.794c	0.235d	0.017d	0.000d
	Continuous	11.2	0.019d	5.265a	4.598a	3.333b	1.469c	0.291d	0.002d
	Intermittent	3.4	0.001c	1.626a	1.536a	1.287a	0.719b	0.101c	0.014c
	Intermittent	11.2	0.001c	4.827a	4.505a	3.785a	1.923b	0.867bc	0.083c

*Values represent average of three replications. Values within a given treatment block not followed by the same letter are significantly different at the 5% level.

TABLE 9

Regression coefficients determined from best fit analysis to first order decay equation.

	Treatments		
Year	*Water mgt.*	*kg/ha molinate*	*Regression Coefficient (r^2)*
1973	Continuous flow	3.4	0.94
	Continuous flow	11.2	0.98
	Intermittent	3.4	0.98
	Intermittent	11.2	0.98
1974	Continuous flow	3.4	0.96
	Continuous flow	11.2	0.99
	Intermittent	3.4	0.86
	Intermittent	11.2	0.98
1975	Continuous flow	3.4	0.99
	Continuous flow	11.2	0.98
	Intermittent	3.4	0.98
	Intermittent	11.2	0.99

TABLE 10

Half-life of molinate in paddy H_2O sampled in 1973, 1974 and 1975 as affected by irrigation management and application rate.

Treatments		*Half-life in hours**		
Water mgt.	*Molinate kg/ha*	*1973*	*1974*	*1975*
Continuous flow	3.4	68	50	45
Continuous flow	11.2	41	63	61
Intermittent	3.4	84	88	100
Intermittent	11.2	73	106	125

*Values averaged over 3 replications.

amounts in the flood water. In 1975, a 0.53 cm rain fell just before the 24-hour samples were collected, and correspondingly resulted in the greatest plot water concentrations. The values decreased markedly between the 24 and 48-hour samples. Two rains totaling 0.79 cm were recorded between the 48 and 96-hour, which may have washed additional material into the water resulting in a second peak in 3 of the 4 treatments at 96 hours. The influence of subsequent rainfall was not evident. The correspondence of peak plot water values and rainfall events, indicated a fraction of the granular material may have lodged in the sheath of the rice foliage.

Application rate and time were found to have a highly significant influence on the amounts of carbofuran in the paddy water in each of the 3 years tested. Irrigation management scheme had no affect on plot water values at the 5% level of significance. The only significant interaction found was between application rate and time. The excessive rate resulted in longer persistence of significant residue levels.

A commercially available formulation of carbaryl was foliarly applied approximately 3 weeks prior to harvest in 1973, 1974, and 1975 (Tables 12, 13, and 14). Peak concentrations correspond to rainfall events. The greatest

TABLE 11

Effect of time, substrate level, and redox potential on the dissipation of molinate in flooded soil samples under laboratory conditions.

Incubation period	*Sucrose added*	*Rep*	*Molinate recovered*	*Eh*
days	g		%	mV
1	none	1	89.1	+167
		2	98.4	+144
	0.25	1	99.5	-183
		2	97.8	-176
	1.00	1	96.7	-208
		2	91.5	-243
	sterilized control†		94.3	+252
8	none	1	92.9	+ 87
		2	85.2	+122
	0.25	1	77.2	+167
		2	72.9	+174
	1.00	1	88.3	- 88
		2	92.8	- 43
	sterilized control†		89.7	+392
16	none	1	30.8	+ 97
		2	69.2	+ 72
	0.25	1	85.7	+ 52
		2	52.9	+ 67
	1.00	1	90.0	- 18
		2	58.9	+ 67
	sterilized control†		89.1	+302

†Sterilized controls had 1 g sugar added to them.

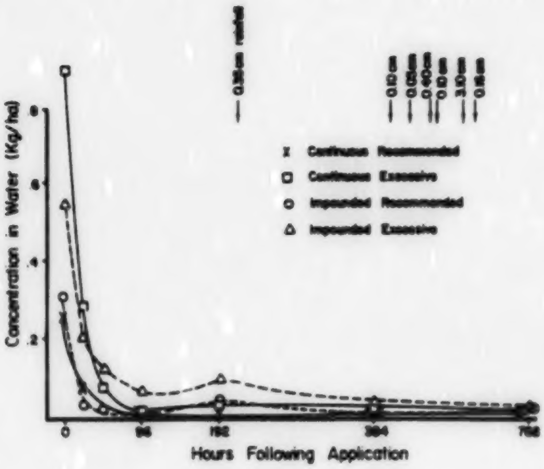

Figure 15. Average concentrations of carbofuran in rice paddy water sampled in 1973.

quantities found in the plot water sampled in 1973 occurred at the 48-hour sampling period, which was preceeded by a 7.6 cm rain. Similar, peak values noted at 40 and 96 hours in 1974 correspond to 8.6- and 0.5-cm rains, respectively. Carbaryl was more evenly dispersed over the first 4 sampling periods in 1974 due to corresponding rains incurred. The amount of carbaryl in the plot water sampled in 1975 peaked 28 hours following application, then was rapidly dissipated over the next 20 hours such that the 48 hour samples did not differ significantly from the 96 hour samples which were essentially zero.

Analyses of variance indicated that time of sample collection and application rate had a highly significant influence on carbaryl levels measured in the water for each of the years tested. Residues of carbaryl were to be greater in those under the intermittent irrigation scheme at a 5% level of significance in 1973, and at a 1% level of significance in 1974. Irrigation treatment had no affect on carbaryl values observed in 1975.

The 24, 48, and 96-hour TLM concentrations for each pesticide showed clearly that the insecticides carbofuran and carbaryl were the most toxic to fish (Table 15), molinate was the least. Plot water concentrations never exceeded these values in the permanent flood released at the end of the growing season. Correspondingly, no

TABLE 12

Concentrations of carbaryl in flood water following its application in 1973, and statistical significance with respect to time.

*Treatment**		*Hours Following Application*					
Block	*Rep*	*0*	*24*	*48* (Kg/ha)	*96*	*192*	*384*
I_1R_1	1	0.160	0.117	0.270	0.001	0.000	0.001
	2	0.055	0.031	0.124	0.001	0.000	0.000
	3	0.095	0.034	0.321	0.000	0.001	0.000
	**ave	0.103a	0.061a	0.238b	0.001a	0.000	0.000
I_1R_2	1	0.119	0.073	0.650	0.000	0.001	0.002
	2	0.073	0.120	0.642	0.001	0.000	0.000
	3	0.171	0.109	0.672	0.006	0.052	0.001
	ave	0.121a	0.101a	0.655b	0.002a	0.027a	0.001a
I_2R_1	1	0.085	0.047	0.563	0.001	0.000	0.002
	2	0.103	0.051	0.396	0.002	0.000	0.000
	3	0.147	0.067	0.222	0.000	0.000	0.000
	ave	0.112a	0.055a	0.394b	0.001a	0.000	0.001
I_2R_2	1	0.119	0.121	0.815	0.573	0.000	0.001
	2	0.161	0.115	0.694	0.000	0.000	0.001
	3	0.513	0.109	1.004	0.000	0.000	0.000
	ave	0.264a	0.115a	0.851b	0.191a	0.000	0.001c

*I_1 and I_2 indicate continuous and impoundment irrigation treatments, respectively. R_1 and R_2 indicate recommended and excessive application rates, respectively.

**Averages with different letter subscripts are significantly different at the 0.01 level.

fish died in the static bioassay test determined on water collected just prior to its release.

However, plot water levels exceeded the TLM value established for carbofuran up to 192 hours following the application at the recommended rate and through the 384 hour sampling period at the excessive rate in 1974 (Figure 16), and 1975 (Figure 17). Impact from runoff within this time frame becomes a function of the quantity of diluent water at the point of release. Although carbaryl exceeded the TLM levels at various sampling periods, the rapidity with which it was degraded certainly lessens its impact as a potential pollutant. Data suggest that propanil and molinate should be of little concern at current recommended rates and cultural practices employed.

The values of TOC, COD, and BOD measured for plot water at the end of each season did not vary significantly from that of the canal water used to irrigate test paddies (Tables 16, 17, and 18).

TABLE 13

Concentrations of carbaryl in paddy water following its application in 1974, and statistical significance with respect to time.

Treatment Block*	*Rep*	*Hours Following Application* 0	24	48	96	168	240
				(kg/ha)			
I_1R_1	1	0.198	0.061	0.498	0.251	0.000	0.000
	2	0.090	0.072	0.032	0.064	0.001	0.000
	3	0.052	0.096	0.007	0.034	0.000	0.000
	**ave	0.113a	0.073a	0.179a	0.113a	0.000a	0.000
I_1R_2	1	0.034	0.125	1.291	0.433	0.000	0.000
	2	0.175	0.090	0.255	0.677	0.015	0.000
	3	0.789	0.068	0.206	0.484	0.000	0.000
	ave	0.333ab	0.094ab	0.584a	0.531a	0.005b	0.000b
I_2R_1	1	0.104	0.039	0.161	0.496	0.000	0.000
	2	0.146	0.015	0.069	0.272	0.000	0.000
	3	0.090	0.020	0.038	0.082	0.000	0.000
	ave	0.113a	0.025a	0.089a	0.288a	0.000a	0.000
I_2R_2	1	0.717	0.173	1.250	0.859	0.002	0.000
	2	1.140	0.659	0.820	0.623	0.000	0.000
	3	1.875	1.807	0.003	1.534	0.473	0.001
	ave	1.244a	0.880ab	0.691b	1.005ab	0.158c	0.000c

*I_1 and I_2 indicate continuous and impoundment irrigation treatments, respectively. R_1 and R_2 indicate recommended and excessive application rates, respectively.

**Averages with different letter subscripts are significantly different at the 0.01 level.

TABLE 14

Concentrations of carbaryl in paddy water following its application in 1975, and statistical signficance with respect to time.

Treatment† Block	*Rep*	*Hours Following Application* 0	21	28	48	96
				(Kg/ha)		
I_1R_1	1	.102	.490	.038	.065	.000
	2	.033	.437	.232	.204	.000
	3	.029	.056	.127	.090	.000
	**ave	.055ab	.328a	.132ab	.120ab	.000b
I_1R_2	1	.079	3.513	7.722	.242	.000
	2	.132	1.407	2.644	.194	.000
	3	.112	.937	1.110	.201	.000
	**ave	.108b	1.980ab	3.832a	.212b	.000b
I_2R_1	1	.025	.181	1.320	.056	.000
	2	.027	.249	.024	.196	.001
	3	.011	.611	.102	.134	.000
	**ave	.021a	.347a	.482a	.129a	.000a
I_2R_2	1	.220	2.368	2.927	.670	.006
	2	.170	.871	.927	2.119	.000
	3	.066	4.476	.300	1.760	.625
	**ave	.152b	2.572a	1.385ab	1.516ab	.210b

†I_1 and I_2 indicate continuous and impoundment irrigation treatments, respectively. R_1 and R_2 indicate recommended and excessive application rates, respectively.

**Averages with different letter subscripts are significantly different at the 0.01 level.

CONCLUSIONS

With normal flooded water management practices, excessive amounts of water are lost to runoff as a direct result of over-irrigation.

TABLE 15

The 24, 48 and 96 hour TLM concentrations and their 95% confidence intervals in filtered tap water in ppm.
1973

Pesticide	*Flow*	*24-Hour*	*48-Hour*	*96-Hour*
Propanil	Static	20.81 (19.68-22.44)	14.51 (13.33-15.65)	7.94 (6.99-6.85)
Molinate	Static	33.25 (31.82-34.96)	33.24 (31.82-34.96)	33.24 (31.82-34.96)
Carbofuran	Static	>1.5 –	1.42 (1.33-1.80)	1.42 (1.29-1.70)
Carbofuran	Intermittent	.56 (.50-.62)	.52 (.47-.58)	.51 (.46-.56)
Carbaryl	Static	6.71 (5.89-7.78)	1.30 (1.24-1.40)	1.30 (1.24-1.70)

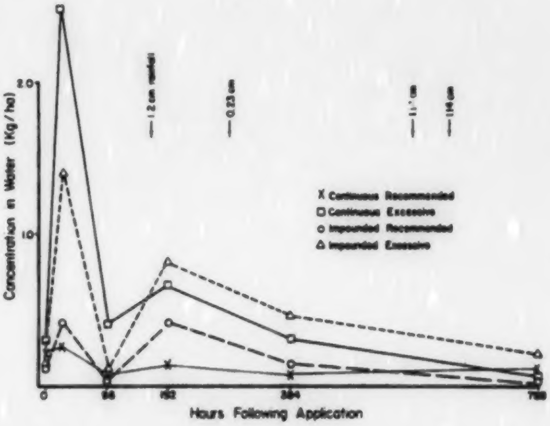

Figure 16. Average concentrations of carbofuran in rice paddy water sampled in 1974.

Losses are greatest in continuous flow systems and may be as great as 1 m during some seasons in the area investigated.

Some pesticides degrade rapidly in the paddy environment, while others persist for several days or weeks after application. Rainfall tends to wash many of the foliar applied chemicals off the plants into the water, causing greater concentration in the runoff after rainfall events than before. For each pesticide tested, the half-life is given and recommendations have been developed for retention times necessary to reduce concentration below toxic limits.

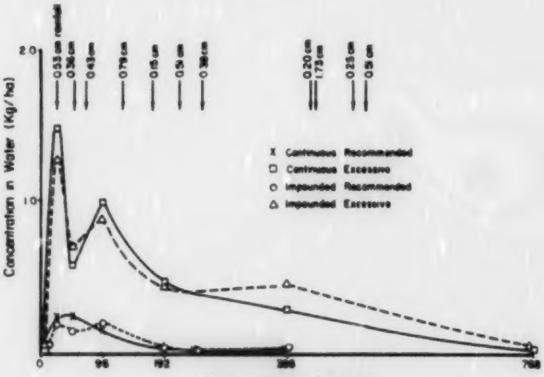

Figure 17. Average concentrations of carbofuran in rice paddy water sampled in 1975.

TABLE 16

Average TOC, COD and BOD of flood water and canal water at the time of final drainage. No significant differences between results were found in any year.

1974

Treatment	*TOC mg/l*	*COD mg/l*	*BOD mg/l*
Impounded irrigation recommended rates of pesticides and nutrients	28	61	2.2
Irrigation recommended rates of pesticides and fertilizers	25.3	57	1.6
Continuous flow irrigation excessive rates of fertilizer and pesticides	29	45.7	2.2
Continuous flow irrigation excessive rates of fertilizer and pesticides	26.7	45	1.6
Canal water	28	55	1.0

TABLE 17

Average TOC, COD and BOD of flood water and canal water at the time of final drainage. No significant differences between results were found in any year.

1975

Treatment	*TOC mg/l*	*COD mg/l*	*BOD mg/l*
Impounded irrigation recommended rates of pesticides and nutrients	29	47	2.1
Irrigation recommended rates of pesticides and fertilizers	23	52	2.2
Continuous flow irrigation excessive rates of fertilizer and pesticides	27	57	1.7
Continuous flow irrigation excessive rates of fertilizer and pesticides	21	48	1.6
Canal water	21	47	2.3

Only a small fraction of the fertilizer nutrients are lost in the runoff water even when runoff volumes are large and excessive amounts of fertilizer have been applied. The soils researched appear to have a large capacity to absorb the nutrients and peak concentrations immediately after application decrease to background levels with three to five days.

Irrigation water use efficiency could be greatly improved with careful management

TABLE 18

Average TOC, COD and BOD of flood water and canal water at the time of final drainage. No significant differences between results were found in any year.

Treatment	*TOC mg/l*	*COD mg/l*	*BOD mg/l*
Irrigation recommended rates of pesticides and fertilizers	11	28	5.3
Continuous flow irrigation excessive rates of fertilizer and pesticides	9.3	25.4	2.0
Border plots intermittent flow irrigation recommended rates of fertilizer and pesticides	13	29.5	6.4
Canal water	17	36	3.4

including the maintenance of small depths of flood and by withholding irrigation water at the end of the season. These practices would reduce irrigation return flow and the decreased water depth in the fields at any given time would allow more volume for storage and would decrease the probability that a rainfall which may occur shortly after a pesticide application would overflow the levees.

ACKNOWLEDGMENT

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Evaluation of Surface Irrigation Return Flows in the Central Valley of California

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ABSTRACT

The variability in the quantity and quality of surface return flows from two typical irrigation districts is reported for the 1975 and 1976 irrigation seasons. Factors contributing to such variations are noted. Emphasis is placed upon the concentration and mass emission of TDS and SS. The implications of these findings are discussed relative to PL 92-500 and best management practices.

INTRODUCTION

The Great Central Valley (Sacramento and San Joaquin Valleys) of California contains about 6.86 million acres of irrigated croplands out of the total 9.1 million acres statewide (3). Field crops (irrigated pasture, alfalfa, cotton, small grains, rice, sugar beets, corn) make up about 70% of this acreage, tree and vine crops (grapes, almond, walnut, peaches, prunes, citrus) about 22%, and vegetable crops (tomato, beans, potato) about 8% (3). On a statewide basis, about 41% of the 9.1 million acres are irrigated by the border method, 34% by furrow, 8% by sprinkler, and the remainder by drip and subirrigation methods (3). The depths of applied water in the Central Valley range from 3.2 to 4.9 ft for field crops, 2.8 to 3.7 ft for tree and vine crops, and 2.4 to 2.7 ft for vegetable crops (3). It has been estimated (2) that about 30% of the applied water in the Sacramento River and San Joaquin River Basins is discharged as surface return flows.

Much attention is now being focused upon irrigation return flows due to recent legislation on water quality and pollution control, and the concerns for water and energy conservation. Figure 1 identifies the major water-flow pathways in the crop root zone portion of irrigated lands and the components of surface return flows; namely, surface runoff (irrigation tailwater, precipitation runoff, operational spills from distribution systems) and collected subsurface drainage (effluents from tile drainage and drainage wells, and subsurface waters intercepted by natural and man-made open channels). With some exceptions, these components of surface irrigation ruturn flows are collected in the same drain regardless of their origin: surface or subsurface, point or nonpoint source. Some of these drain waters are reused, either planned or incidental, at the site of production or downstream, while the remainder is discharged with no readily apparent beneficial uses. It should be noted that surface irrigation return flows in California are nearly nonexistent where water is scarce and/or expensive.

This report presents some data on the flow and quality characteristics of surface irrigation returns from two typical irrigation districts for the 1975 and 1976 irrigation seasons. Differences in the quantity and quality of return flows are noted, with particular regards to total dissolved solids (TDS) and suspended solids (SS), and attempts are made to relate these differences to site specific factors and conditions. In addition, the information and data are evaluated with regards to PL 92-500 and potential best management practices.

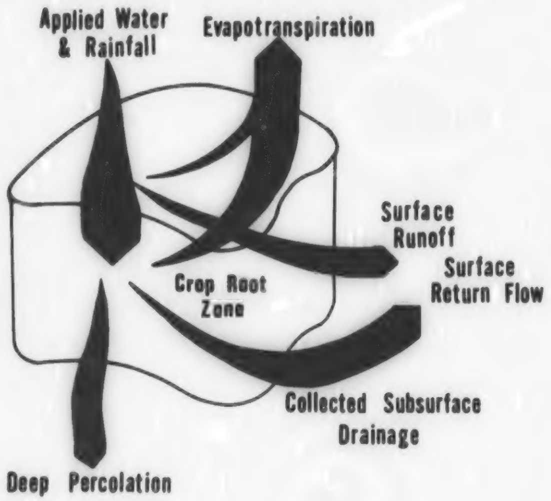
Applied Water & Rainfall
Evapotranspiration
Surface Runoff
Surface Return Flow
Crop Root Zone
Collected Subsurface Drainage
Deep Percolation

Figure 1. The major water-flow pathways in the crop root zone portion of irrigated lands. Surface return flow is comprised of surface runoffs and collected subsurface drainage.

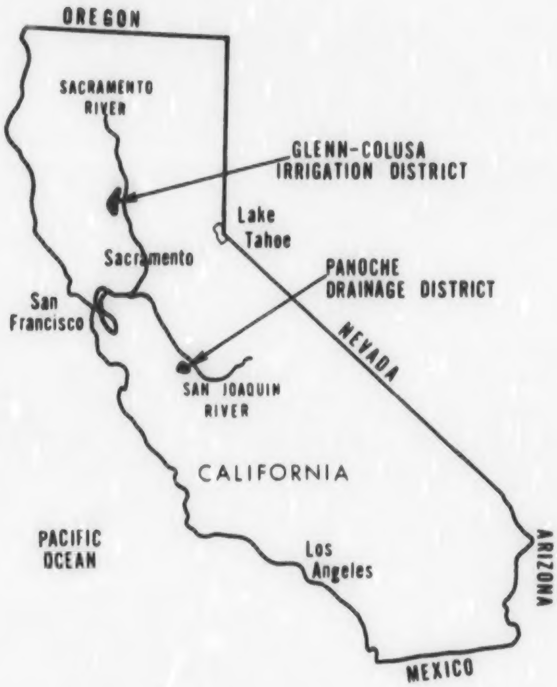
OREGON
SACRAMENTO RIVER
GLENN-COLUSA IRRIGATION DISTRICT
Lake Tahoe
Sacramento
San Francisco
PANOCHE DRAINAGE DISTRICT
NEVADA
SAN JOAQUIN RIVER
CALIFORNIA
PACIFIC OCEAN
Los Angeles
ARIZONA
MEXICO

Figure 2. Location map pointing out two study areas in the Great Central Valley of California.

DESCRIPTION OF STUDY AREAS

Figure 2 gives a location map of the two irrigation districts considered, Glenn-Colusa Irrigation District (GCID) in the Sacramento River Basin and Panoche Drainage District (PDD) in the San Joaquin River Basin. GCID, Figure 3, is a 163,700 acre district that obtains its supply waters by diversions from the Sacramento River and Stony Creek, and discharges its return flows via 11 lateral drains into the 70-mile Colusa Basin Drain (CBD), which has an outfall to the Sacramento River above Knights Landing as well as to the Yolo Bypass. PDD, Figure 4, is a 43,800 acre district that receives imported water from the Sacramento River Basin via the Delta-Mendota Canal and the California Aqueduct. Its return flows are discharged mainly into the

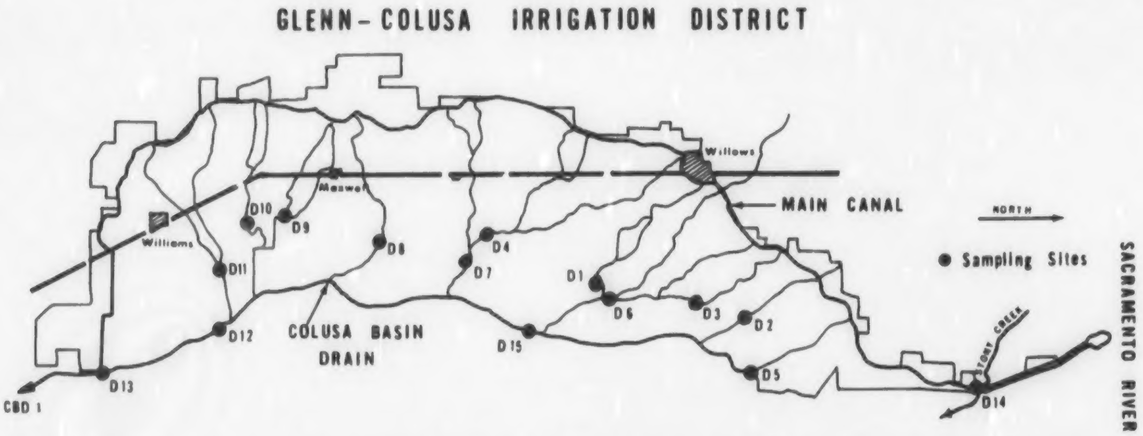
GLENN-COLUSA IRRIGATION DISTRICT
Willows
Maxwell
Williams
MAIN CANAL
NORTH
Sampling Sites
SACRAMENTO RIVER
STONY CREEK
COLUSA BASIN DRAIN
CBD 1
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
D14
D15

Figure 3. Map of the 163,700 acre Glenn-Colusa Irrigation District in the Sacramento River Basin of California.

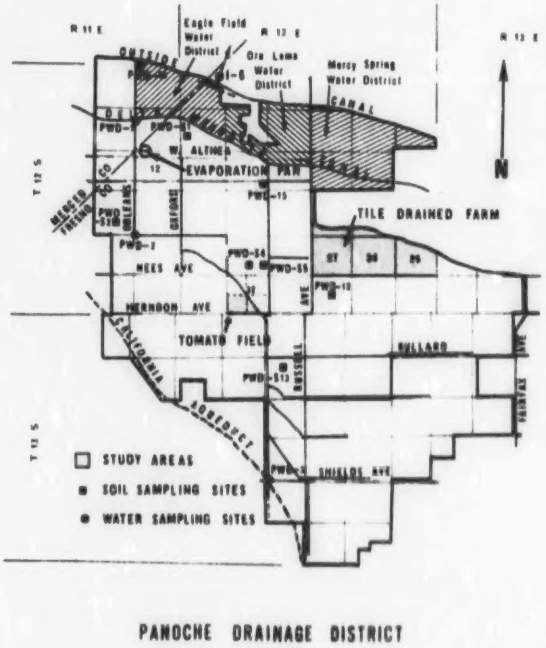
R 11 E
Eagle Field Water District
R 12 E
R 13 E
Ora Loma Water District
Mercy Spring Water District
OUTSIDE
CANAL
I-6
PWD-1
PWD-21
W. ALTHEA
EVAPORATION PAN
12
PWD-15
T 12 S
MERCED
FRESNO
CO.
PWD-S2
ORLEANS
GEORGE
TILE DRAINED FARM
27
28
29
PWD-7
PWD-34
PWD-35
NEES AVE
PWD-12
AVE
HERNDON AVE
CALIFORNIA
AQUEDUCT
TOMATO FIELD
BULLARD
AVE
RUSSELL
PWD-S13
FAIRFAX
T 13 S
STUDY AREAS
SOIL SAMPLING SITES
WATER SAMPLING SITES
PWD-3
SHIELDS AVE
PANOCHE DRAINAGE DISTRICT

Figure 4. Map of the 43,800 acre Panoche Drainage District in the San Joaquin River Basin of California.

Grasslands Water District (GWD) for reuse by irrigated pastures and waterfowl habitats, and ultimately discharged into the middle reaches of the San Joaquin River. Other significant reuse of return flows discharged into the Sacramento and San Joaquin Rivers is also made by downstream users.

The major crop grown in GCID is rice (70% of irrigated acreage in 1975 and 58% in 1976) which is continuously flooded throughout the growing season. Irrigation usually begins in April and ends in October. The major crops grown in PDD are cotton, tomatoes, and melons which are furrow irrigated, and barley and wheat which may receive some pre-irrigation or irrigation depending upon winter rainfall. In PDD irrigation is practiced year-round, except in November and December when the usual maintenance and repairs take place.

WATER QUANTITY AND QUALITY

Table 1 gives detailed analyses of the supply and drain waters based upon the average of 3 to 4 grab samples taken over each irrigation season. The quality of the supply waters for GCID is excellent while the drain waters have not been degraded significantly. In contrast, for PDD the supply waters are similar to the quality of drain waters from GCID and its drainage waters are substantially degraded with regards to dissolved mineral salts, turbidity, nitrogen, and boron. Table 2 describes differences in quality characteristics for the several components of collected surface irrigation return flows relative to the supply water. The substantial degradation of drain waters from PDD may

TABLE 1

Quality of supply and drain waters in Glenn-Colusa Irrigation District (GCID) and Panoche Drainage District (PDD)

Quality parameters	*GCID, 1975*		*GCID, 1976*		*PDD, 1975*		*PDD, 1976*	
	Supply	*Drain*	*Supply*	*Drain*	*Supply*	*Drain*	*Supply*	*Drain*
EC, micromhos/cm	117	418	133	386	389	2.779	473	2,891
Solutes in meq/liter								
Na	0.22	1.92	0.32	1.86	1.75	15.3	2.09	16.7
Ca	0.50	1.22	0.45	1.20	1.22	8.55	1.16	8.58
Mg	0.40	1.39	0.46	1.48	0.97	3.90	1.05	4.75
HCO_3	0.99	3.00	1.18	3.26	1.57	3.22	1.71	3.03
Cl	0.07	0.48	0.10	0.54	1.41	11.6	2.01	12.1
SO_4	0.08	0.85	0.08	0.91	0.76	13.8	0.91	14.7
Turbidity, JTU	9	25	6	23	31	125	24	180
BOD_5,mg/liter	3.0	2.6	0.9	2.2	0.6	0.6	1.1	1.2
Nitrogen in mg N/liter								
Total N	0.92	1.31	0.83	1.29	1.13	13.5	1.43	17.1
Org. N	0.87	1.03	0.71	1.00	0.46	0.70	0.75	1.44
NH_4	0.03	0.07	0.04	0.15	0.05	0.10	0.04	0.19
NO_3	0.14	0.19	0.10	0.17	0.62	12.6	0.64	13.4
Boron, mg/liter	—	—	—	—	0.12	4.3	0.11	4.4

TABLE 2

Collected surface irrigation return flow components and their quality characteristics as related to applied waters.

Quality parameters	*Operational spills*	*Irrigation tailwater*	*Subsurface drainage*
General quality	0	+	++
Salinity	0	0, +	++
Nitrogen	0	0, +, ++	++, +
Oxygen demanding organics	0	+, 0	0, -, --
Sediments	0, +, -	++	--
Pesticide residues	0	++	0, -, +
Phosphorus	0	++	0, -, +

0 = not expected to be much different than

+, - = some slight increase/pickup or decrease/deposition may occur.
++ = usually expected to be significantly higher due to concentrating effects, application of agricultural chemicals, erosional losses, pickup of natural geochemical sources, etc.
-- = usually expected to be significantly lower due to filtration, fixation, microbial degradation etc.

be largely attributed to the collected subsurface drainage which is affected by the presence of native soil salts, boron and nitrogen, and the production of sediments from the highly erodible Panoche soils (6).

Figures 5 and 6 show monthly flows and concentrations of TDS and SS for supply and drain waters in GCID and PDD, respectively (6, 7). The 1975 irrigation season was in a "normal" hydrologic year while the 1976 irrigation season was in a "drought" hydrologic year. The flows of supply and discharge waters in GCID are dominated by flooded rice culture. Rice is planted in late April to early May and irrigated until late August to early September, which is reflected by the flows in Figure 5. The drain outflow is usually characterized by peak flows in the early and late irrigation periods. The former is due to lowering of water levels in rice fields to prevent erosion of levees by gusty winds that usually occur in May and the latter is due to the draining of rice fields prior to harvesting in mid-September and early October. The peak irrigation and drain outflow months in PDD usually occur between March and August for field and vegetable crops, but water is delivered year-round because of less precipitation in PDD than in GCID (7.73 and 10.65 inches in PDD during October through September for 1974/75 and 1975/76 hydrologic years vs. 19.56 and 6.58 inches in GCID, respectively) and to some extent double cropping.

Figures 7 and 8 contain schematic diagrams for supply and surface drain waters for both the 1975 and 1976 irrigation seasons in GCID and PDD, respectively. Included in these diagrams are seasonal quantities of supply water and their sources; gross quantities of

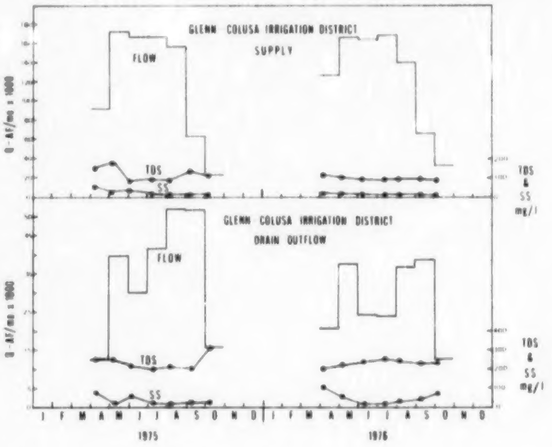

Figure 5. Monthly flows of supply and drain waters in Glenn-Colusa Irrigation District over two irrigation seasons and concentrations of total dissolved solids and suspended solids.

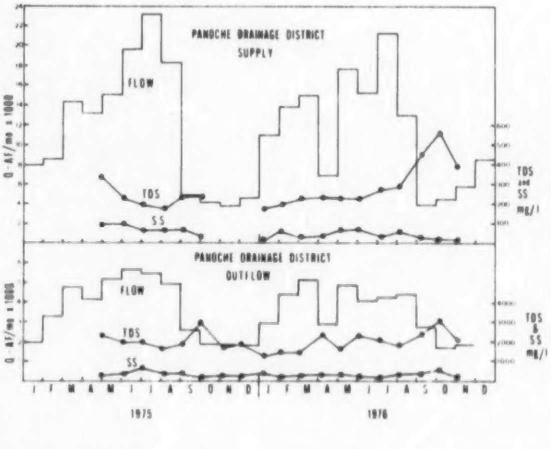

Figure 6. Monthly flows of supply and drain waters in Panoche Drainage District over two irrigation seasons and concentrations of total dissolved solids and suspended matter.

drainage, part of which are captured and reused within the district and remainder discharged; irrigated acreages; unit application and unit drainage rates (acre-feet / acre); and corresponding masses (concentration x water volume) of TDS and SS (tons); as well as unit mass application and unit mass emission rates (tons / acre). It is not possible herein to fully discuss these data, but an attempt will be made to point out the major findings.

In GCID, an increase of 7,800 acres of irrigated lands occurred between 1975 and 1976 with a corresponding increase in diverted water, but the unit application rate was slightly less (6.31 vs. 6.18 acre-feet / acre) due mainly to a reduction of 12,136 acres in rice. In contrast, there was a decrease of 2,870 acres of irrigated lands in PDD from 1975 to 1976 and a corresponding decrease in imported water, but the unit application rates were nearly the same. Of the 465,400 and 398,500 acre-feet of drain water produced in GCID in 1975 and 1976, respectively, about half of it was captured and reused within the district. The net discharge of surface irrigation return flow was 29 and 21% of diverted water in 1975 and 1976, respectively. For comparison, PDD recaptured only 3.5 and 10.4% of their drain waters from the 1975 and 1976 irrigation season, respectively. Central California Irrigation District (CCID) also used 16.8 and 19.3% of PDD's drain waters in 1975 and 1976, respectively. The remainder of the surface return flows were discharged into the Grasslands Water District (GWD). The unit drainage rate was 0.91 and 0.85 acre-feet / acre for these two irrigation seasons in PDD as compared to 1.84 and 1.31 acre-feet / acre in GCID. These differences may be largely attributed to irrigation application methods and crop culture.

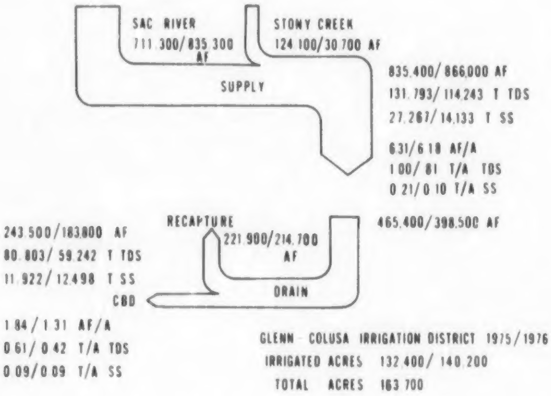
SAC RIVER
711.300/835.300 AF
STONY CREEK
124.100/30.700 AF
SUPPLY
835.400/866.000 AF
131.793/114.243 T TDS
27.267/14.133 T SS
6.31/6.18 AF/A
1.00/.81 T/A TDS
0.21/0.10 T/A SS
RECAPTURE
221.900/214.700 AF
465.400/398.500 AF
243.500/183.800 AF
80.803/59.242 T TDS
11.922/12.498 T SS
CBD
DRAIN
1.84/1.31 AF/A
0.61/0.42 T/A TDS
0.09/0.09 T/A SS
GLENN - COLUSA IRRIGATION DISTRICT 1975/1976
IRRIGATED ACRES 132.400/140.200
TOTAL ACRES 163.700

Figure 7. A schematic diagram of seasonal surface inflow and surface outflow of water, salts, and sediments over two irrigation seasons in Glenn-Colusa Irrigation District.

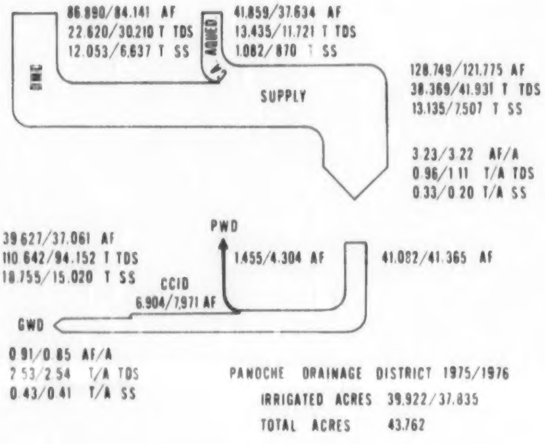
86.890/84.141 AF
22.620/30.210 T TDS
12.053/6.637 T SS
DMC
AQUED
41.859/37.634 AF
13.435/11.721 T TDS
1.082/870 T SS
SUPPLY
128.749/121.775 AF
38.369/41.931 T TDS
13.135/7.507 T SS
3.23/3.22 AF/A
0.96/1.11 T/A TDS
0.33/0.20 T/A SS
PWD
39.627/37.061 AF
110.642/94.152 T TDS
18.755/15.020 T SS
1.455/4.304 AF
41.082/41.365 AF
CCID
6.904/7.971 AF
GWD
0.91/0.85 AF/A
2.53/2.54 T/A TDS
0.43/0.41 T/A SS
PANOCHE DRAINAGE DISTRICT 1975/1976
IRRIGATED ACRES 39.922/37.835
TOTAL ACRES 43.762

Figure 8. A schematic diagram of seasonal surface inflow and surface outflow of water, salts, and sediments over two irrigation seasons in Panoche Drainage District.

The monthly flow-weighted average concentration of TDS (mainly dissolved mineral salts) in GCID's supply water was 116 and 97 mg/liter and drain water 244 and 237 mg/liter for the 1975 and 1976 seasons, respectively, about a 2.1- and 2.4-fold increase in concentration. In contrast, the TDS in PDD's supply water was 219 and 254 mg / liter and drain water 2,053 and 1,868 mg / liter for the 1975 and 1976 seasons, respectively, and a 9.4- and 7.4-fold increase. But, on a mass basis, Figure 7 for GCID indicates only 61 and 52% of the TDS in 1975 and 1976 irrigation water, respectively, were discharged into CBD while Figure 8 for PDD indicates 288 and 225% for the corresponding values. With regards to TDS, the increase in concentration of TDS in drain water relative to the supply water for GCID is in the usual range of 2- to 4-fold increase from the evapotranspiration concentrating effects by crop plants. The remainder of salts brought in by the irrigation water presumably is lost as deep percolation since accumulation of salts in soils is not observed. On the other hand, the 9.4- and 7.4-fold increase in the concentration of TDS in PDD's drain waters must be attributed to the pickup of salts through chemical weathering of native soil salts and minerals. Soil analyses (6) from PDD show that EC_e typically ranges from 1.6 millimhos/cm in soils containing large amounts of gypsum (greater than 10 T/AF). Results from a conceptual hydrosalinity model (4) indicate gypsum contributes about 25 meq/liter of salts (2,152 mg/liter TDS) to the soil solution. Furthermore, this computer model indicates if gypsum was not present, the TDS of surface irrigation return flow from PDD would be 458 mg/liter instead of the monitored 2,053 mg/liter in 1975. For comparison, the computer predicted 1,818 mg/liter in the presence of gypsum.

The monthly flow-weighted average concentration of SS (mainly sediments) in GCID's supply water was 24 and 12 mg/liter and drain water 36 and 50 mg/liter for the 1975 and 1976 irrigation seasons, respectively. But the mass of SS discharged into Colusa Basin Drain (CBD), Figure 7, was 44 and 88% of that brought into the district from the supply water. Likewise, SS in PDD's supply water was 75 and 45 mg/liter and drain water 348 and 298 mg/liter for the 1975 and 1976 irrigation seasons, respectively, a 4.6- and 6.6-fold increase in concentration. However, on a mass basis, Figure 8, the SS discharged into GWD and CBD was 1.4 and 2.0 times the amount brought into the district from their supply water. The difference in unit mass emission rate of SS from GCID as compared to PDD may be attributed to the fact that flooded rice fields in GCID more or less act as settling basins for SS while the soils in PDD are highly erodible (6).

DISCUSSION

The implications of the above evaluations on concentration and mass emission of TDS and SS are of considerable importance. While it is recognized that impact of pollutants on the beneficial uses of waters may be appraised in terms of concentration, the effectiveness of controlling discharge of pollutants should not only be considered in terms of concentration but also on a mass emission basis. If concentration is overly stressed, this tends to promote inefficient water management (5).

A survey (5, 6) of typical ranges of variations in the quality and quantity of surface irrigation return flows along with the data presented herein indicates the quantity and quality of surface irrigation may be highly variable and site specific. This particular conclusion should be considered for irrigation return flows (point or nonpoint, collected or uncollected) when contemplating future water quality and pollution controls. Some of the principal factors affecting how much irrigation return flows are generated include: availability and cost of supply water; irrigation application methods and efficiencies; extent of reuse of drain waters at the onfarm, district and basin levels; soil physical conditions; and special cultural practices such as the lowering of water in flood rice fields during strong winds to prevent erosion of levees to germination of seeds in furrow beds. Some of the principal factors affecting the quality of surface irrigation return flows are: quality of supply water; presence of native soil salts, boron and nitrogen; leaching fraction and salt pickup-salt deposition phenomena; use of agricultural chemicals such as fertilizers and soil amendments; insecticides and herbicides, animal manures and wastewaters; crop and other plant residues; erodibility of surface soils and open drain channel banks; sedimentation and resuspension of suspended matter as affected by current velocity and size fraction; and discharges into irrigation drainage canals by other sectors of society including other agricultural activities, municipal and industrial treatment plants, silviculture, rangelands and watersheds.

In our opinion irrigated agriculture is a unique institutional structure for which effluent guidelines and "end of the pipe" controls promulgated in PL 92-500 cannot be applied as reasonably as in most other industries. It is our contention that irrigated agriculture does not have the "plumbing and valves" found in industrial and sewage treatment plants. Irrigated agriculture operates in an "open system" in contrast to a "closed system" (as in most other industries). Many of the natural conditions and processes under which irrigated agriculture operates are unmanageable or uncontrollable by man, or, at best, difficult to control. Thus, if irrigated agriculture is to comply with the intent of PL 92-500, this industry will require pollution abatement controls and policies different from those of most other industries.

It is suggested that due considerations instead be given to "best management practices" rather than concentrating on waste discharge requirements. A recent publication (1) points out alternative control and management practices for surface irrigation return flows. Since irrigation tailwater is considered to be easiest to control of the components of surface irrigation return flows, tailwater management appears to be a logical best management practice. However, the effects of tailwater discharge into surface waters may be either beneficial, detrimental, or both, depending on the quality constituents of interest and water flow. Be that as it may, for application to Central Valley conditions, Figure 9 presents an array of alternative controls on tailwater production and potential pollution of surface receiving water bodies (5). Some of these tailwater management practices may be broadly applicable, while others are not because they require extensive structural modifications and/or costly water control. Due to the site variability of receiving waters and of tailwater production and quality, it is difficult to recommend any single universally applicable best management practice. A practice that is effective in one location may not be as effective in another.

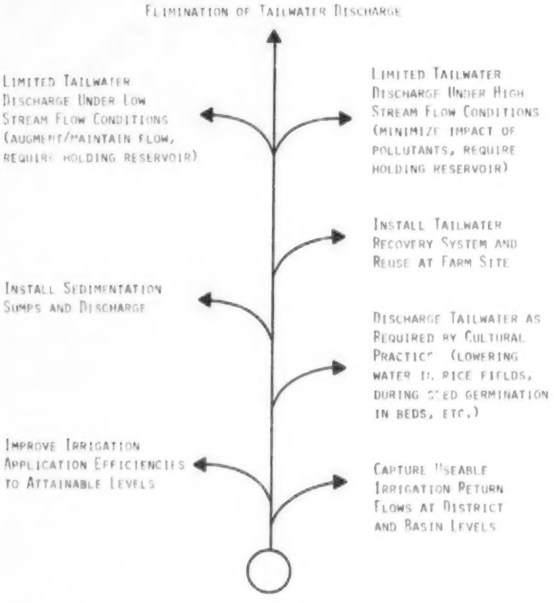
Elimination of Tailwater Discharge
Limited Tailwater Discharge Under Low Stream Flow Conditions (Augment/Maintain Flow, Require Holding Reservoir)
Limited Tailwater Discharge Under High Stream Flow Conditions (Minimize Impact of Pollutants, Require Holding Reservoir)
Install Tailwater Recovery System and Reuse at Farm Site
Install Sedimentation Sumps and Discharge
Discharge Tailwater as Required by Cultural Practice (Lowering Water in Rice Fields, During Seed Germination in Beds, etc.)
Improve Irrigation Application Efficiencies to Attainable Levels
Capture Useable Irrigation Return Flows at District and Basin Levels

Figure 9. An array of potential best management practices for the control of irrigation tailwater and potential pollution of surface receiving water bodies.

ACKNOWLEDGMENT

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An Economic Analysis of Irrigation Return Flow Recycle Systems in the Central Valley of California

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ABSTRACT

Irrigation return flow recycle systems have been used in California for a number of years under a variety of crop rotations, soil characteristics and qualities of irrigation water. Recycle systems operating on the field, farm and district level were compared on the basis of cost in two areas of the San Joaquin Valley. The effects of three scales of recycle systems on the least-cost combination of irrigation water delivery systems and water management techniques were evaluated.

INTRODUCTION

In an annual progress report to the Environmental Protection Agency, it was concluded that the production of tailwater occurred in irrigated areas where water costs were low, water supplies plentiful, high water use did not affect yields and facilities for tailwater disposal existed (Tanji, 1976, p. 18). The report also recommended that the amount of tailwater could be reduced by either adopting more efficient water application methods or managing the present systems more carefully.

Public Law 92-500 has established water quality goals that could require a substantial reduction in the amount of disposed tailwater. Therefore, determining the cost of alternative methods of reducing tailwater is important in selecting a least cost policy to achieve the goals established in PL 92-500. This paper contains an evaluation of farm and field level irrigation methods and systems used in the San Joaquin Valley that eliminate or substantially reduce the amount of tailwater produced.

Irrigated agriculture uses about 85 percent of the developed water in California and about 75 percent of the state's irrigation water is used in the Central Valley. Field crops dominate the Central Valley agriculture and about 90 percent of them are irrigated by border and furrow methods.

A reliable estimate of the amount of tailwater produced in the Central Valley does not exist. In 1975, the Central Valley Regional Water Quality Control Board required many of the irrigated areas to have a permit for the disposal of irrigation return flows. The permit requires the monitoring and reporting of the flow, electrical conductivity and suspended solids of supply and discharge waters. These results will provide more insight into irrigation efficiencies in the Central Valley and facilitate a more comprehensive economic evaluation of tailwater disposal.

CONTROLLING TAILWATER IN A FIELD

Furrow irrigation typically produces runoff in a field of 20 to 40 percent of the water applied (Tanji, 1976, p. 16). Attempts to reduce the stream of water to control runoff usually result in poor water distribution and reduced crop yields. The installation of a tailwater reuse system can eliminate runoff by collecting the tailwater in a sump at the lower end of the field and pumping it back to the head of the field for reuse. The reuse system allows maximum stream flow, water penetration and high irrigation efficiency.

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Most field crops currently using border or furrow irrigation methods could be irrigated with some type of sprinkler system. Sprinkler systems require more capital than nonpressurized systems but are more efficient in water application, require less labor and, with good management, will reduce tailwater substantially.

The cost of restricting tailwater losses from a 170 acre tomato field was estimated by comparing the costs of a conventional furrow irrigation system with three systems that essentially eliminate tailwater. They are a furrow irrigation operation using gated pipe and a reuse system, a handmove sprinkler system and a side roll sprinkler system.

The conventional furrow irrigation system utilized earth head ditches, canvas dams and 1-1/2 inch siphons. The field was leveled annually and the cost per acre of irrigating the tomato crop was $177.21 (Table 1). No reuse system was employed and five acre-feet of water per acre was applied to the crop.

The second system was also a furrow system, but instead of earth head ditches, gated pipe was utilized with a settling pond and a reuse pump. The total amount of water used was reduced from five acre-feet to 3.75 acre-feet per year. This reduction in water use was measured on a 170 acre tomato field located in the Panoche Water District. The amount and quality of water applied, tailwater and water reuse were monitored in 1975. The tailwater, as a percent of applied water, was 28.7 percent for the field and 24 percent for a specific 63 furrow section of the field (Tanji, 1976, p. 84). Therefore, the water recovery factor of 25 percent was used in calculating costs for this system. Limited resources and errors in other monitoring efforts prevented replicating these measurements as planned. However, these results seem to be within the observed limits of other reuse systems.

The cost of irrigating the tomato field with this system was $150.25, or almost $27.00 less than the conventional furrow system. Investment per acre increased from $7.74 to $249.00 per acre and labor decreased from $135 to $90 per acre.

The cost of irrigating the tomatoes by the hand move sprinklers was $152.21. Although the capital requirements were less than the gated pipe-reuse system, operating costs were slightly higher.

The side roll sprinkler system resulted in costs of $127.79 per acre. Capital requirements were high compared to the other systems but only one hour of labor per acre per irrigation is needed to operate the system. This is considerably less than the other irrigation methods considered.

TABLE 1

Summary of Irrigation Costs per acre for
170 acres of Tomatoes by Irrigation Method
Panoche Water District, 1976

	Furrow with Siphons and no Reuse System	*Furrow with Gated Pipes and Reuse System*	*Side Roll Sprinkler*	*Hand Move Sprinkler*
		Dollars Per Acre		
Investment	7.74	249.00	291.37	165.88
Depreciation[2]	.65	9.97	19.39	10.98
Interest	.31	9.96	11.67	6.63
Taxes	.16	4.98	5.83	3.33
Total Overhead	1.12	24.91	36.89	20.94
Operating Costs:				
Irrigation Preparation	10.76	9.38	— —	— —
Water Requirement	5.00AF	3.75AF	3.75AF	3.75AF
Water Cost	30.00	22.50	22.50	22.50
Labor ($4.50/hr.)	135.00[1]	90.00	45.00[1]	90.00[1]
Repairs	.33	.34	11.65	6.64
Power	— —	3.12	10.34	9.35
Lateral Installation and Removal	— —	— —	1.41	2.78
Total Operating Cost	176.09	125.34	90.90	131.27
Total Cost	177.21	150.25	127.79	152.21

[1] Reed, A. D., Jewell L. Meyer and Falih K. Aljibury, "Irrigation Costs," Cooperative Extension University of California, Leaflet 2875, Davis, Aug. 1976.

[2] An 8 percent interest rate and straight line depreciation was used. Specific cost budgets are presented in the appendix.

These data indicate that irrigation systems designed to apply water efficiently and without the production of significant tailwater is also the least-cost alternative. These results probably could be achieved in most other areas of the Central Valley because the physical conditions in the test area are fairly representative. The cost of water used in this analysis was $6.00 per acre-foot which is relatively cheap. The higher the cost of water the greater the cost savings from using the more water efficient systems. If water were free, a conventional furrow system would compare more favorably with the more efficient systems, but the high labor requirement of operating siphons and canvas dams result in high operating costs.

The internal rate of return was approximated for the three irrigation systems that are capable of controlling tailwater. The savings in irrigation costs as a result of using the three systems was used as the annual return. The internal rate of return for the gated pipe and reuse system was approximately 18 percent; the side roll sprinkler system, 16 percent; and the hand move sprinkler system, 16.5 percent. The investment in more efficient irrigation systems appears to be profitable. However, a relatively few California irrigators have adopted field recycle systems or sprinkler irrigation systems. The reasons farmers have not widely adopted field recycle systems may be a topic of further research.

MANAGEMENT OF DRAINAGE WATER AT THE FARM LEVEL

The problem of managing irrigation return flows in the San Joaquin Valley is complicated by high water table conditions in many locations (San Joaquin Valley Interagency Drainage Program). In the Panoche Soil Conservation District, water table elevations have been rising steadily for a number of years (Stoddard & Kaner). The Enrico farm, located within this district, has been recycling a mixture of surface runoff and subsurface tile drainage water since 1969. A normative linear programming analysis was developed based on the actual operations of the Enrico farm. The objective of the LP problem is to derive cropping patterns and water use that maximize returns to land and management for the model farm, subject to restraints on crop rotation, quantity and quality of applied water, and resource availability.

Model Formulation

The Enrico farm is 1,675 acres in size with an entitlement to 5025 acre-feet of district water. District water is taken from the supply canal near the lower end of the farm where it may be mixed with return-flows before the mixture is pumped to the upper end for application. The quality of applied water can be varied by using different proportions of project and recycled water.

The surface and subsurface return-flows are collected in a District drainage ditch located on the farm's boundary. In addition, due to uphill discharges into this drain, the farm has access to additional drainage water for recycling purposes. In order to represent a variety of conditions for available uphill runoff, the model was run with levels ranging from 0 to 3000 acre-feet.

Gross revenues for cropping activities were determined using area average prices and yields from the period 1970 to 1976. Net revenues were then derived by subtracting typical crop production costs (University of California Cooperative Extension). Water activities were defined for the application of project and recycled water. The costs of running these activities were then subtracted from crop revenues in the objective function. The cost of pumping return-flows back to the fields was assumed to be \$3.50 per acre-foot. Model solutions were derived using a range of prices for project water, varying from \$5.00 to \$25.00 per acre-foot.

Crop alternatives include tomatoes, wheat, barley, cotton, alfalfa seed, sugar beets, and dry beans. The crops were separated into three classes according to their yield tolerance to the boron concentration of applied water (University of California Committee of Consultants). For each boron tolerance level, limits are set on the maximum proportion of return-flows in applied water that will avoid yield reductions. These limits are based on flow-weighted average boron concentrations as measured on the Enrico farm during the 1975 and 1976 irrigation seasons. District water had a flow weighted average boron concentration of 0.1 mg/l, compared to about 2.5 mg/l for recycled water. Total dissolved solids of these waters were low. Therefore, considering the boron tolerance of crops was sufficient in determing the yield reduction from TDS (University of California Committee of Consultants) solutions were also derived using an assumed boron concentration of 10 mg/l in drainage water, to reflect conditions where the subsurface component was a higher proportion of total return-flows.

Water application and runoff rates are based on values estimated by the California Department of Water Resources. Maximum acreage rectrictions were included to reflect rotational and crop contract requirements.

Model Results

Optimal project and drainage water use, cropping patterns and returns per acre for the farm were derived for various water prices and amounts of external drainage water supplied (Table 2). Assuming a \$5.00 District water cost and 3,000 acre feet of district return flows, drainage water use was 3,382 acre-feet, or 68 percent of total water use. If a \$20.00 District water cost is assumed, the amount of drainage

TABLE 2

Optimal Cropping Pattern and Drainage Water Use with Zero, 1,000 and 3,000 Acre-Foot of Drainage Water Available and Project Water Costing $5.00 and $20.00 per Acre-Foot. Enrico Brother's Farm, Panoche Irrigation District.

	District Water Costs/Acre-Foot					
	$5.00	*$20.00*	*$5.00*	*$20.00*	*$5.00*	*$20.00*
Drainage Water Available (Acre-Foot)	3,000	3,000	1,000	1,000	0	0
Drainage Water Use (Acre-Foot):						
High Quality Blend	1,000	1,000	633	1,101	0	1,101
Medium Quality Blend	1,777	1,169	1,777	1,309	1,410	309
Low Quality Blend	607	2,180	380	380	380	380
Total	3,382	4,349	2,790	2,790	1,790	1,790
Percent of Total Water Use	68	76	57	57	37	37
Drainage Water Discharged	1,363	396	0	0	0	0
Project Water Use (Acre-Foot):						
High Quality Blend	1,000	1,000	1,570	1,101	2,203	1,101
Medium Quality Blend	523	344	523	991	890	1,991
Total	1,523	1,344	2,092	2,092	3,092	3,092
Total Water Applied (Acre-Foot)	4,905	5,693	4,882	4,882	4,882	4,882
Cropping Pattern (acres):						
Tomatoes	500	500	500	500	500	500
Wheat	600	75	600	600	600	600
Cotton	400	400	400	400	400	400
Alfalfa Seed	75	600	0	0	0	0
Sugar Beets	100	100	100	100	100	100
Dry Beans	0	0	75	75	75	75
Total	1,675	1,675	1,675	1,675	1,675	1,675
Returns Per Acre	336	322	335	316	334	306

water used for irrigation increased to 4,349 acre-feet, or 76 percent of total water use. Average returns decreased from $336 to $322 per acre, as a result of the higher cost of water and the change in the cropping pattern from wheat to alfalfa seed which has a higher tolerance to boron. Total water application increased from 4,905 to 5,693 acre-feet.

If external drainage water supplies are decreased below 3,000 acre-feet, changes in project water costs do not affect the amount of drainage water reused. With 1,000 and zero acre-feet of extra drainage water available, respectively, 57 percent and 37 percent of the total applied water is composed of drainage water. This represents total reuse of farm and off-farm return-flows.

CONCLUSIONS

The amount of field tailwater can be reduced significantly and the annual costs of irrigation slightly reduced by adopting reuse or sprinkler application systems. However, the high capital requirements of $165 to $300 per acre may prevent the adoption of such techniques. For example, installing a hand move sprinkler system or a side roll system on 160 acres would require $26,540 and $46,620, respectively. Although the annual irrigation costs are lowered with these systems, the purchase of such a system may not be the optimal investment if capital is limited. Greater returns may be realized from investment in land or machinery. More efficient use of irrigation water would also result if water prices were increased, or the quantity of water decreased.

The profitability of augmenting the farm water supply with drainage water depends on the costs of both District water and recycle system. Generally, the higher the cost of irrigation water the greater the value of drainage water. Assumming a $20.00 cost of irrigation water, returns could be increased by $16.00 per acre by pumping an additional 2,604 acre-feet of drainage water from the District's drainage canal. The optimal water supply would consist of 75 percent drainage water. At a $5.00 water cost about 68 percent of the optimal irrigation water supply would be drainage water.

APPENDIX

TABLE A-1

Per Acre Cost of Furrow Irrigating a 170 Acre Tomato Field with Siphons and No Reuse System.

	Annual Cost						
	Cost	*Cost Acre*	*Life*	*Depreciation*	*Interest*	*Taxes*	*Total*
Investment						*Dollars Per Acre*	
Pitcher, 54"	2,100	2.63	20	.13	.11	.05	.29
Siphons, 1½-300	475	1.36	10	.14	.05	.03	.22
Canvass, 12	350	1.00	5	.20	.04	.02	.26
Ditch Closer	2,200	2.75	15	.18	.11	.06	.35
Total Overhead		7.74		.65	.31	.16	1.12
Operating Costs:							
Irrigation Preparation:							
Fuel and Repairs				6.02			
Labor (.75/Acre)				3.36			
Total Leveling					9.38		
Ditch Open & Close:							
Fuel & Repairs				.82			
Labor (.12/Acre)				.54			
Total Ditch Costs					1.36		
Total Irrigation Preparation						10.76	
Irrigation: (10X)							
Labor (30 hours/acre)				135.00			
Water (5 Acre-Foot)				30.00			
Repairs				.33			
Total Irrigation						165.33	
Total Operating Costs							176.09
Total Irrigation Cost							177.21

TABLE A-2

Per Acre Cost of Furrow Irrigating a 170 Acre Tomato Field with Gated Pipe and a Reuse System.

	Annual Cost						
	Cost	*Cost Acre*	*Life*	*Depreciation*	*Interest*	*Taxes*	*Total*
Investment:	*Dollars Per Acre*						
PVC Pipes:							
15″	10.560	66.00	30	2.20	2.64	1.32	6.16
10″ or 12″	3,300	21.00	30	.70	.84	.42	1.96
Gated Pipes	18,744	117.00	30	3.90	4.68	2.34	10.92
Pump[1]	4,000	25.00	10	2.50	1.00	.50	4.00
Settling Pond[1]	3,250	20.00	30	.67	.80	.40	1.87
Total		249.00		9.97	9.96	4.98	24.91
Operational Costs:							
Irrigation Preparation:							
Leveling:							
Fuel and Repairs			6.02				
Labor (.75/Acre)			3.36				
Total Irrigation Preparation					9.38		
Irrigation: (10X)							
Labor (20.00 hours/acre)			90.00				
Water (3.75 (Acre Foot)			22.50				
Power for Recirculation			3.12				
Fuel & Repairs			.34				
Total Irrigation					115.96		
Total Operating							125.34
Total Irrigation Costs							150.25

[1]Source: Ray Ram, Manager, Panoche Irrigation District, Firbaugh CA.

TABLE A-3

Per Acre Cost of Irrigating a 170 Acre Tomato Field with a Side Roll Sprinkler System

	Annual Cost						
	Cost	*Cost Acre*	*Life*	*Depreciation*	*Interest*	*Taxes*	*Total*
Investment:	*Dollars Per Acre*						
Aluminum Pipe:							
10"	4,642.70	27.31	15	1.82	1.09	.54	3.45
8"	3,478.20	20.46	15	1.36	.82	.41	2.59
Hydrant Valves	535.50	3.15	20	.16	.13	.06	.35
Pump	10,062.50	62.50	15	4.17	2.50	1.25	7.92
Laterals	30,395.00	178.13	15	11.88	7.13	3.57	22.58
		291.37		19.39	11.67	5.83	36.89
Operating Costs:							
Irrigation (10X)							
Labor (10. hours/acre)			45.00				
Water (3.75 AF)			22.50				
Power			10.34				
Repairs (4%)			11.65				
Total Irrigation					89.49		
Lateral Installation & Removal:							
Fuel & Repair			.71				
Labor			.70				
Total Lateral Installation & Removal					1.41		
Total Operating Costs							90.90
Total Irrigation Costs							127.00

TABLE A-4

Per Acre Cost of Irrigating a 170 Acre Tomato Field with a Hand Move Sprinkler System

	Annual Cost						
	Cost	*Cost Acre*	*Life*	*Depreciation*	*Interest*	*Taxes*	*Total*
Investment:	*Dollars Per Acre*						
Aluminum Pipe:							
10"	4,642.70	27.31	15	1.82	1.09	.55	3.46
8"	3,478.20	20.46	15	1.36	.82	.41	2.59
Hydrant Valves	814.30	4.79	20	.24	.19	.10	.53
Pump	10,062.50	62.50	15	4.17	2.50	1.25	7.92
Laterals	8,639.40	50.82	15	3.39	2.03	1.02	6.44
		165.88		10.98	6.63	3.33	20.94
Operating Costs:							
Irrigation (10X)							
Labor (20 hours/acre)			90.00				
Water (3.75 AF)			22.50				
Power			9.35				
Repairs (4%)			6.64				
					128.49		
Lateral Installation & Removal:							
Fuel & Repairs			1.40				
Labor			1.38				
Total Lateral Installation & Removal				2.78			
Total Operating Costs							131.27
Total Irrigation Costs							152.21

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On-Farm Methods for Controlling Sediment and Nutrient Losses

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ABSTRACT

Field experiments were conducted in the Boise and Magic Valley areas of southern Idaho during the 1975 and 1976 irrigation seasons to evaluate on-farm methods for controlling sediment and nutrient losses from irrigated fields. In one experiment, four 1.7 ha plots of field corn were continuously monitored during the two irrigation seasons. Varying furrow stream sizes and stream cutback methods were used to apply the same total amounts of irrigation water to three of the plots. No control measures were used on the fourth plot. Runoff from two of the first three plots was run through a vegetated buffer strip at the lower end of the field and then a settling basin. Runoff from the other two plots was run through a basin only. The effects of each treatment and control measure on the quality and quantity of return flow from these plots are presented.

Sediment yield from bean field plots which were subjected to three different levels of cultivation was evaluated during the 1975 and 1976 seasons. The effects of zero, one and two cultivations on seasonal sediment yield, return flow quantities and phosphate loss were determined. During the 1976 irrigation season, surface runoff from the bean field plots was passed through three sizes of mini-basins at the lower end of the field. The basins were six feet wide and collected runoff from three, four and five furrows. The efficiency of duplicate mini-basins was evaluated with and without grassed overflow sections on the drain ditch bank.

The results of sediment and nutrient yield determinations on several other field sites in the two study areas are also presented. The effects of various combinations of soil types, crops, irrigation practices and sediment retention devices on sediment and nutrient losses from these sites were evaluated.

INTRODUCTION

The importance of irrigation in producing crops in arid and semi-arid regions of the world is well documented. This practice is particularly important to western areas of the United States where irrigation is required for the production of most crops. While beneficial in many respects, irrigation can have serious detrimental effects on water quality since irrigation return flows may contain dissolved salts, sediment, plant nutrients, and other materials. The effects of these materials on the quality of receiving waters are a major concern in the western states since irrigation return flows constitute a large portion of the flow in many streams in this region.

The major water quality problem in most western irrigated areas is increased salt concentrations in the return flow as a result of the pickup of minerals from the soils and the loss of water through evapotranspiration (6). As a result, a number of studies have been conducted to find ways to decrease the concentration of salt in return flows in these areas. Salinity is not a major problem, however, in many irrigated areas. Instead, the major problem is sediment in the surface runoff from irrigated fields; and, to a lesser extent, nitrate and other nutrients in ground and surface waters in these areas.

There are a number of ways in which sediment and nutrient losses from irrigated areas can be effectively controlled. These include the use of irrigation and/or other practices which eliminate or reduce surface runoff and resulting pollutant losses from individual fields and on-the-farm removal of sediment and nutrients from the surface runoff from individual fields. Field investigations to determine the effectiveness of several on-farm methods for controlling sediment and nutrient losses from fields were conducted in two irrigated areas in southern Idaho during the 1975 and 1976 irrigation seasons. Data obtained from these investigations are presented and discussed in the following paragraphs.

STUDY AREAS

The field investigations were conducted in two major irrigated areas in southern Idaho, the Boise Valley in southwestern Idaho and the Magic Valley in southcentral Idaho. Both of these areas have a dry, temperate climate which is characterized by cool, wet winters and warm, dry summers. Broad expanses of nearly level or gently sloping lands in these areas are suitable for intensive cultivation. Most of these lands are used for growing irrigated row crops, grain, and forage crops.

The Boise Valley lies in an upland plain of unconsolidated lacustrine and fluvial materials deposited by the Snake and Boise Rivers. Terraces of stream-laid and lacustrine deposits rise stepwise above the Boise River. In several areas, local basalt ridges rise as much as 122 meters above the bottom land. The soils in the area are highly variable and complex. Those over the alluvial materials are generally quite variable in depth. Duripans in many of the soils restrict the downward movement of water and plant roots. High water tables are common in many valley areas.

Most of the farms in the Boise Valley are gravity irrigated, primarily through the use of siphon tubes and furrow methods. Sprinkler irrigation is practiced in the valley, although its use is not very extensive at present. Irrigation return flows are collected by a complex network of open ditch drains. Many of these drains return all or a portion of their flow to the delivery system for reuse. A number of crops including alfalfa and clover for seed and hay, grain, field corn, sweet corn, beans, potatoes, sugarbeets, and onions are grown in the valley. Hops, mint, and several other specialty crops are also grown and some of the area is used for orchards.

Most of the irrigated land in the Magic Valley lies in a region designated as the Snake River Plain aquifer. Land north of the river is underlain by the Snake Plain aquifer. Land south of the river slopes northward from foothills and is underlain by basalts and rhyolites at varying depths. The major soils in the area are of loessal origin with calcareous loamy subsoils. The silt loam soils are generally underlain by a calcareous hardpan at a depth of 60 to 90 cm. This cemented layer is permeable but restricts root penetration.

Water for irrigation is obtained from the Snake River and is conveyed to farms in the valley through unlined canals. Water application is predominantly by gravity systems through the use of siphon tubes and furrows. The use of gated pipe is increasing and sprinkler irrigation from ground or surface water sources is common in the area. The use of pumpback systems is also increasing. The principal crops grown in the area are sugarbeets, beans, grain, alfalfa, and potatoes.

FIELD INVESTIGATIONS

Most of the field investigations in the Boise and Magic Valley areas were carried out on gravity-irrigated fields at University of Idaho Research and Extension Centers at Caldwell and Kimberly respectively. A few investigations were also conducted on cooperators' fields in the two study areas.

Boise Valley Investigations

Four field plots were monitored during the 1975 and 1976 irrigation seasons to determine the effects of different irrigation water management practices and on-farm sediment retention devices on the quantity and quality of the surface runoff from these plots. Descriptions of the plot sites are given in Table 1. Sites 2, 3, and 4 were located adjacent to each other in a large field at the Caldwell Center. Site 1 was located in a cooperator's field on land adjacent to the Caldwell Center. The soil at all four sites is a silt loam which is underlain by a cemented hardpan at a depth of 75 cm or less. The erosion hazard for this soil is moderate to high. Field corn was grown on all four plots, both in 1975 and 1976.

TABLE 1

Boise Valley Field Plot Site Descriptions

Site	*Year*	*Area (ha)*	*Run Length (m)*	*Average Slope (%)*	*Sediment Retention Device(s)*
1	1975	1.76	237	2.6	Pond
	1976	1.76	237	2.6	T-Slot & Pond
2	1975	1.89	345	2.7	Pond
	1976	1.78	345	2.7	Grain Strip & Pond
3	1975	1.84	327	2.9	Grass Strip & Pond
	1976	1.74	327	2.9	Grain Strip & Pond
4	1975	1.76	321	2.9	Grass Strip & Pond
	1976	1.66	321	2.9	Grain Strip & Pond

As indicated in Table 1, the surface runoff from each plot was diverted through one or more sediment retention devices. In 1976, for example, the runoff from Site 1 flowed through a series of small T-shaped Basins (T-Slots) before entering a small sediment pond. These basins were installed at 20-meter intervals upstream from the pond. In 1975, the runoff from Sites 3 and 4 passed through a grass strip before it entered a sediment pond. Densely seeded barley was used as a buffer strip at Sites 2, 3, and 4 in 1976.

All flows entering each plot or sediment retention device were continuously monitored during the 1975 and 1976 irrigation seasons. Weirs and flumes equipped with stage recorders were used to obtain continuous records of these flows. Water samples were taken from the headwater and surface runoff from each plot and from the flow leaving each sediment retention device at regular intervals during each irrigation. Data obtained from this monitoring program were used to establish water and mass balances for each site. The components of the mass balances included sediment, nitrate, and total phosphorus. The balance results were summarized for each irrigation, each set within an irrigation, and the entire season.

Magic Valley Investigations

Field and plot studies were conducted at five locations in the Kimberly area to evaluate sediment and phosphate reduction for alternative management practices and sediment removal systems. Included were studies of (1) cultivation and water management practices (tillage study), (2) mini-basins, (3) vegetated buffer strips, (4) sediment removal by a dense growing crop, and (5) furrow cutback irrigation. In making these studies, weirs and flumes were used to make the necessary flow measurements. Water samples taken at appropriate stations were used to determine the concentrations of sediment in the flows. In general, the flow and concentration data were used as input to a computer program for determination of flow volumes and sediment yields for each study site for each irrigation.

RESULTS AND DISCUSSION

Boise Valley Investigations

Water, sediment, and nutrient losses from the study sites were affected by the water management practices and sediment retention devices used at these sites. Evaluations were made to determine the effects of different furrow stream sizes, preplant irrigations, irrigation scheduling, vegetated buffer strips, and sediment retention ponds on these losses.

Furrow Stream Size

The plots at Sites 2, 3, and 4 were irrigated five times during the 1976 irrigation season with different sizes of furrow streams. Stream size and pollutant loss data for each site are given in Table 2. A stream of 0.767 liters per second was used to irrigate Site 2 during the first three irrigations. This stream was reduced to approximately 0.6 liters per second during the last two irrigations to limit runoff. At Site 3, the furrow stream was cut back to one-half its initial size after 12 hours during the first three irrigations. During the last two irrigations, the

TABLE 2

Results of Boise Valley Furrow Stream Size Study, 1975 and 1976

Site	*Irrigation*	*Set Length (hr)*	*Stream Size (l/s)*	*Net Sediment Loss (kg/ha)*	*Net Total P Loss (kg/ha)*	*Net Nitrate Loss (kg/ha)*
2	1	24	0.767	2456	1.42	0.09
3	1	36	0.767,0.384[1]	1647	1.36	0.07
4	1	48	0.396	-656[2]	-0.17	-0.18
2	2	24	0.767	395	0.04	-0.26
3	2	36	0.767,0.384	744	0.60	-0.15
4	2	24	0.407	-508	-0.06	-0.33
2	3	24	0.767	183	-0.06	-0.37
3	3	36	0.767,0.384	155	0.29	-0.32
4	3	48	0.407	-140	-0.19	-0.35
2	4	24	0.599	200	0.15	-0.06
3	4	24	0.599	142	0.01	-0.20
4	4	24	0.609	69	-0.07	-0.45
2	5	24	0.599	24	-0.03	-0.50
3	5	24	0.600	105	0.0	-0.37
4	5	24	0.643	123	0.01	-0.40

[1] Stream was cutback to smaller flow rate after 12 hours.

[2] Negative numbers indicate a net gain.

furrow stream was reduced to approximately 0.6 liters per second but was not cut back. A stream of approximately 0.4 liters per second was used to irrigate Site 4. This stream had to be increased to over 0.6 liters per second during the last two irrigations to get the wetting front to advance properly.

The sediment loss during the first irrigation of the season is usually greater than it is during subsequent irrigations (5). This was the case for Sites 2 and 3. However, the sediment loss from Site 3 (with cutback) was almost one third less than the loss from Site 2 (without cutback) during the first irrigation. The sediment losses from both sites were much less during the last four irrigations than they were during the first irrigation. The seasonal totals (Table 3) show that the net sediment loss from Site 3 (with cutback) was over 16 percent less than the net loss from Site 2 (without cutback). The use of a small stream size on Site 4 resulted in a net gain of sediment on this plot during the first three irrigations. However, the sediment losses during the last two irrigations were nearly the same as those from the other two sites. The overall effect of using a reduced stream size during the first three irrigations is shown by the seasonal total which indicates a net sediment retention of over 1,100 kg/ha on this plot.

TABLE 3

Seasonal Totals for the Boise Valley Furrow Stream Size Study, 1975 and 1976.

Site	*Net Sediment Loss (kg/ha)*	*Net Total P Loss (kg/ha)*	*Net Nitrate Loss (kg/ha)*
2	3258	1.52	-1.10[1]
3	2793	2.26	-0.97
4	-1112	-0.48	-1.71

[1] **Negative numbers indicate a net gain.**

The runoff from all three plots was sampled after it had passed through a vegetated buffer strip and had flowed to the sampling point in a ditch which had a slope of 0.5 percent. As a result, a portion of the sediment retention shown for these sites occurred in the buffer strip and in the drainage ditch.

Total phosphorus losses from Sites 2 and 3 were minimal. The net retention of total phosphorus on Site 4 is related to the net sediment retention, since total phosphorus losses are associated with sediment losses (2, 4). The net retention of nitrate at all three sites was due to the fact that nitrate is infiltrated into the soil with the irrigation water. Similar results have been obtained at other sites in the Boise Valley (1, 3).

Preplant Irrigation

Many irrigators apply a preplant irrigation regardless of the soil moisture status. In order to evaluate the effects of this practice, preplant irrigations were applied to Sites 2, 3, and 4 ten days before the 1976 crop was planted. Water and sediment loss data for these irrigations are summarized in Table 4. The data show that a large amount of sediment was lost from each plot even though the runoff was not excessive. Over one-third of the seasonal sediment loss from Sites 2 and 3 occurred during the preplant irrigation. The amount of sediment lost from Site 4 during the preplant irrigation was nearly equal to the net amount returned on that plot during the remainder of the irrigation season (Table 3).

TABLE 4

Effects of Preplant Irrigations on Water and Sediment Losses, 1976

	Water Runoff		*Net Sediment Loss*		
Site	*Preplant Irrigation (mm)*	*Percent of Seasonal Runoff*	*Preplant Irrigation (kg/ha)*	*Seasonal[1] Loss (kg/ha)*	*Percent of Seasonal Loss*
2	41	16	1773	5031	35
3	52	23	1657	4450	37
4	69	36	1188	76	1563

[1] **Seasonal total includes preplant irrigation loss.**

Irrigation Scheduling

Irrigation scheduling can have an effect on sediment and nutrient losses from a field as well as an effect on crop yields (1). If a field is over-irrigated or irrigated too frequently, the resulting surface runoff will be excessive and will carry excessive amounts of sediment and other pollutants from the field. Reducing the number of irrigations and the amount of water applied will usually reduce the losses from a particular field. This was the case for Site 1. The number of irrigations at the site was reduced from eight in 1975 to six in 1976, partially as a result of a 15 percent decrease in the consumptive use requirements of the crop. As shown in Table 5, reducing the number of irrigations resulted in a 21 percent reduction in the amount of water applied, a 31 percent reduction in the amount of surface runoff, and 25 percent reduction in the net amount of sediment lost from the plot.

TABLE 5

Effects of Number of Irrigations on Water and Sediment Losses

Year	Number of Irrigations	Consumptive Use (mm)	Water Applied (mm)	Water-Use[1] Efficiency (%)	Surface Runoff (mm)	Net Sediment Loss (kg/ha)
1975	8	510	1270	40.1	376	26,565
1976	6	432	1000	43.2	261	19,923

[1] Percentage of water applied going to consumptive use.

The water-use efficiencies (percentage of water applied used to meet the consumptive use requirements of the crop) were quite low both years. However, these efficiencies are about as high as can be expected for a furrow system operating under the soil, slope, run length, and other conditions present at this site. They could be increased by the installation and use of a pumpback system.

Vegetated Buffer Strips

In 1975, a sodded grass strip which was 1.83 m wide and 61.0 m long was laid in the drainage ditch at the lower end of Site 3. The runoff from Site 3 entered the strip from the side while that from Site 4 entered the strip from the upper end and ran the entire length of the strip. Samples of the runoff from both sites were collected downstream from the strip. The runoff from the control plot, Site 2, did not run through the strip.

Dense bluegrass in the strip was well established and approximately 2.4 cm high just prior to the first irrigation. The strip did an excellent job of reducing the velocity of flow in the drain ditch during the first irrigation. As a result, it was completely inundated with sediment and was not effective during the remainder of the irrigation season. The effectiveness of the strip during the first irrigation is shown by the data in Table 6. About 47 percent of the net seasonal sediment loss from Site 2 (without strip) occurred during the first irrigation; whereas, only about 19 and 8 percent of the losses from Sites 3 and 4 (with strip), respectively, occurred during the first irrigation. Due to the ineffectiveness of the grassed strip, the net losses during the last four irrigations were essentially the same for all three sites.

In 1976, a 2.44 m wide strip of barley was seeded across the lower ends of the three plots at a seeding rate of approximately 100 kg/ha. The grain was well established when the irrigation season was started and was effective in retarding the furrow runoff and causing sediment to settle out of the runoff before it entered the drain ditch running parallel to the strip. The effectiveness of this strip is shown by the data presented in Table 6. Site 2 was irrigated nearly the same in 1976 as it was in 1975. Most of the difference in the total net sediment loss (3258 kg/ha in 1976 as opposed to 7038 kg/ha in 1975) can be attributed to the effect of the buffer strip used in 1976. Although the net loss from Site 2 during the first irrigation in 1976 was nearly as great as the loss during the first irrigation in 1975, use of the grain strip resulted in a marked decrease in the net sediment losses during the last four irrigations. The totals in Table 6 indicate that the grain strip used in 1976 was more effective than the grassed strips used on Sites 3 and 4 in 1975.

TABLE 6

Effects of Vegetated Buffer Strips on Sediment Losses

Site	Year	Strip Type	Irrigation Number(s)	Net Sediment Loss (kg/ha)
2	1975	none	1	3312
			2-5	3726
			total	7038
3	1975	grass	1	740
			2-5	3149
			total	3889
4	1975	grass	1	367
			2-5	4196
			total	4563
2	1976	grain	1	2456
			2-5	802
			total	3258

Sediment Retention Ponds

Sediment retention ponds were used to remove a portion of the sediment and phosphorus from the surface runoff from the four plots before it flowed from the study sites. In 1976, six small T-shaped basins (T-slots) were also installed in the drain ditch upstream from Site 1. Four of the T-slots had a capacity of approximately 2 m^3 while the other two had a capacity of about 0.5 m^3. The six T-slots were filled with sediment during the first irrigation and were ineffective thereafter. The effectiveness of the T-slots and pond during the first irrigation is shown by the data presented in Table 7.

TABLE 7

Sediment and Phosphorus Removal by T-Slots and Sediment Pond at Site 1 During the First Irrigation, 1976

Constituent	*Into T-Slots (kg/ha)*	*Into Pond (kg/ha)*	*Out of Pond (kg/ha)*	*Removal by T-Slots (%)*	*Removal by T-Slots & Pond (%)*
Total Phosphorus	0.73	0.33	0.24	45	78
Sediment	1055	504	189	48	66

The sediment retention ponds were quite effective in reducing the net sediment losses from all four field sites. Seasonal sediment balances for the four field plots and the ponds are given in Table 8. The sediment removal efficiency of the ponds ranged from 46 to 82 percent. One reason for the low removal efficiency of the pond at Site 1 in 1975 was the small size of this pond. It was essentially filled with sediment by the first two irrigations in 1975. With the added retention of the T-slots in 1976, the pond did not fill with sediment until after the third irrigation. Even though the pond was ineffective for over half of the irrigation season each year, it did greatly reduce the net sediment loss from this site.

All of the runoff from Sites 2, 3, and 4 was diverted through the same pond. The data in Table 9 show that the sediment removal efficiency of this pond was quite high both years. This pond was large enough that it did not require cleaning after the 1975 season and was only about half filled with sediment at the end of the 1976 season. Of course, the irrigation management practices and vegetated strips described previously helped reduce the amount of sediment entering this pond.

Magic Valley Investigations

The results obtained from the Magic Valley field investigations also show that water and pollutant losses from gravity-irrigated field sites were significantly affected by the management practices and sediment retention devices used at these sites. Like the results of the Boise Valley investigations, they indicate the need for integrating the use of management practices with the use of sediment retention devices to minimize losses.

Tillage Study

An evaluation of the effects of cultivation and irrigation practices on water and sediment losses from a dry bean field was made in 1975 and 1976. A 1.5-hectare field at the Kimberly Center was used for this study. The soil at this location is Portneuf silt loam with field slopes varying from 0.8 to 1.2 percent. Two methods of preplant irrigation were used to prepare the field for planting. In one case, a "broadcast" procedure was used to wet the entire field surface.

TABLE 8

Seasonal Sediment Balances for the Field Plots and Sediment Ponds, 1975 and 1976

						Net Loss	
Site	*Year*	*On Plots (kg/ha)*	*Off Plots*[1] *(kg/ha)*	*Out of Pond (kg/ha)*	*Removal by Pond (%)*	*w/o Pond (kg/ha)*	*with Pond (kg/ha)*
1	1975	621	27,146	14,710	46	26,525	14,089
	1976	482	20,405	6,273	69	19,923	5,791
2	1975	1,051	8,088	1,425	82	7,038	374
	1976	1,004	4,262[2]	770	82	3,258	-234[3]
3	1975	1,352	5,241	934	82	3,889	-418
	1976	775	3,568[2]	888	75	2,793	113
4	1975	1,652	6,215	1,232	80	4,563	-420
	1976	1,787	675[2]	261	61	-1,112	-1,526

[1] Includes effects of T-slots and vegetated buffer strips.

[2] Does not include preplant irrigation.

[3] Negative numbers indicate a net gain.

In the other, a "banded" procedure was used to wet only the seedbed area. After planting, the two preplant irrigation treatments were split into three cultivation treatments which were cultivated 1, 2, or 3 times in 1975 and 0, 1, or 2 times in 1976. Each of the 30 plots in the field was irrigated at 8 to 12-day intervals. A total of eight irrigations were applied in 1975. The 1976 experiment was terminated after a hailstorm destroyed the crop during the sixth irrigation.

The results from the 1976 experiment show that significant differences in sediment yield occurred between the two preplant irrigations. In fact, the yield from the broadcast treatment was 1,050 kg/ha while that from the banded treatment was only 260 kg/ha. This difference is to be expected since the furrow spacing for the broadcast treatment was much less than that for the banded treatment (11.8 versus 18.9 cm). As a result, the runoff and resulting sediment losses per unit area from the broadcast treatment were greater than those from the banded treatment. The results also show that field slope had a significant effect on sediment yield. This is shown by the regression equations presented in Figure 1 for the five 1976 irrigations. As can be seen, the sediment yield from the steeper field slopes apparently increased as the irrigation season progressed.

Statistical analyses of the 1975 and 1976 data show that there was no significant correlation between the number of cultivations performed and total sediment yield. Also, the irrigation application efficiency (percentage of water applied which is retained on a field) was not significantly correlated with the number of cultivations. The data do show, however, that there is an inverse relationship between the seasonal gross sediment yield from the bean field and irrigation application efficiency. A plot of the gross sediment yield versus application efficiency for the 13 irrigations performed in 1975 and 1976 is shown in Figure 2. This relationship illustrates one of the basic concepts in reducing sediment losses from gravity-irrigated fields. Generally, any practice which increases irrigation efficiency results in a decrease in sediment losses.

Mini-Basins

In 1976, a mini-basin study was conducted on a 1.38 hectare bean field adjacent to the tillage study field. A total of 12 basins were installed by construction of berms perpendicular to the bank of the drain ditch along the lower end of this field to form small shallow ponds. The basins were varied in size so as to collect the flow from 3, 4, or 5 furrows and were constructed with either plastic or grassed overflow sections. The overflow sections were 0.5 wide and were leveled to provide uniform flow over the section. Five irrigations were monitored to obtain data for determining the sediment removal efficiency of the basins.

The data obtained from this study are summarized in Table 9. The seasonal sediment loss from the field, as indicated by the average of the check furrow losses, would have been 14,950 kg/ha. The weighted average loss for the mini-basins was only 680 kg/ha. The average seasonal sediment removal efficiency of the basins was 94.9 percent.

There is apparently no significant difference in the sediment removal efficiency of the

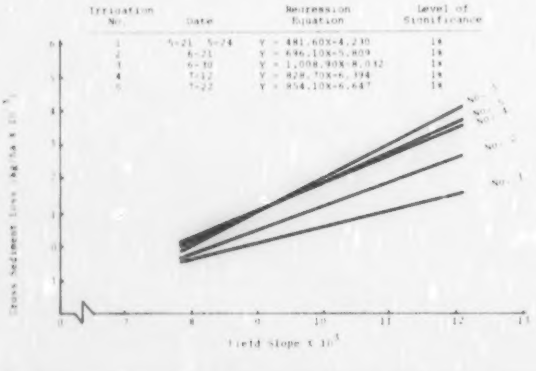

Figure 1. Regression equations for field slope on gross sediment yield for five irrigations of a bean field near Kimberly, Idaho, 1976.

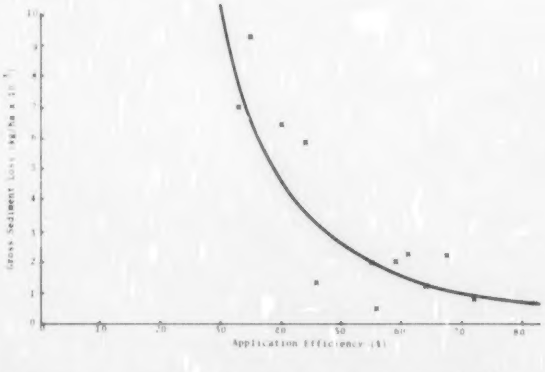

Figure 2. Sediment yield versus application efficiency for a bean field near Kimberly, Idaho, 1976.

different sizes of mini-basins used in this study even though the average depth of the larger basins was less than that of the smaller basins. There is also no apparent benefit to using a grassed overflow section instead of a plastic section. It is doubtful that a farmer would spend the time and money to install plastic sections. However, grassed overflow sections should be relatively easy to manage, and constuction of simple grassed overflow mini-basins can provide an economical means of retaining sediments on a field.

One of the 3-furrow basins was filled with sediment after five irrigations. This indicates that the larger 4 or 5-furrow basins are more likely to remain effective over a full season.

TABLE 9

Results of Magic Valley Mini-Basin Study, 1976

Basin	*Basin*[1] *Size*	*Overflow Type*	*Sediment Yield (kg/ha)* *Basins*	*Sediment Yield (kg/ha)* *Check Furrows*	*Removal Efficiency (%)*
1	3	grass	930	13,480	93.2
2	3	plastic	690	16,540	95.4
3	4	grass	400	14,670	96.4
4	4	plastic	720	11,080	93.3
5	5	grass	630	17,720	96.3
6	5	plastic	770	16,180	95.0

[1] Number of furrows entering basin.

Vegetated Buffer Strips

The vegetated buffer strip study was conducted in 1976 on a 1.8-hectare spring wheat field at the Kimberly Center. Flow and sediment yield data for the three plots established at this site are summarized in Table 10. Plot 1 was the check plot. Plot 2 was banded with a single planting of springwheat while Plot 3 was banded with a double planting. These bands or strips were 2.4 m wide. The plots were all the same size (approximately 0.6 hectares). The slopes of the three plots were 1.2, 1.4, and 1.7 percent respectively. Each plot was irrigated six times using 6.5-hour sets.

The total amounts of water applied to the three plots ranged from 501 mm on Plot 2 to 535 mm on Plot 1. The runoff ranged from 148 mm on Plot 3 to 162 mm on Plots 1 and 2. The average net application to the three plots was 359 mm. The seasonal water application efficiencies for the three plots were essentially all the same. The seasonal sediment yields, on the other hand, varied considerably — from 1828 kg/ha for Plot 3 (double planted) to 8618 kg/ha for the check plot.

TABLE 10

Seasonal Totals for the Magic Valley
Buffer Strip Study, 1976

Plot	*Stand Density (stems/m^2)*	*Inflow (mm)*	*Outflow (mm)*	*Application*[1] *Efficiency (%)*	*Sediment Yield (kg/ha)*
1	519	535	162	70	8,618
2	739	501	162	68	3,411
3	815	514	148	71	1,828

[1] Percentage of inflow retained on plot.

As can be seen from the data presented in Table 10, increasing the stand density of the wheat resulted in a large reduction in sediment yield. In fact, increasing the stand density from 519 to 815 stems/m ^{2} (an increase of 57 percent) resulted in over a four-fold reduction in the sediment yield. Non-significant differences between plots in the total amounts of water applied and the application efficiencies indicate that retardation of flow in the buffer strips was sufficient to remove sediment but did not increase infiltration appreciably. Planting the buffer strips required very little effort and did not disrupt normal irrigation and farming operations.

Sediment Removal by Alfalfa

A cooperator's 1.5-hectare field of alfalfa was monitored during 1975 to determine the magnitude of sediment reduction obtainable when surface runoff is reused for irrigation. The field was 146 m long and had an average slope of 1.7 percent respectively. Each plot was irrigated six times using 6.5-hour sets.

The results obtained from this monitoring program are presented in Table 11. The net amount of water applied during the four irrigations was 657 mm. The application efficiencies ranged from 85 percent for the third irrigation to 95 percent for the first irrigation. The average for the season was 88 percent. The average sediment concentration of the outflow was 340 mg/l while that of the inflow was 170 mg/l. The net sediment removal varied from 42 percent for the first irrigation to 97 percent for the fourth irrigation, and averaged 79 percent for the season. These results show that utilization of sediment laden runoff to irrigate a dense growing crop such as alfalfa is a viable method for improving water quality and retaining sediments on farm fields.

TABLE 11

Results of Sediment Removal by Alfalfa Study, 1975

	Water			*Sediment*		
Irrigation	*Inflow (mm)*	*Outflow (mm)*	*Application[1] Efficiency (%)*	*Inflow (kg/ha)*	*Outflow (kg/ha)*	*Removed (%)*
1	172	8	95	125	45	64
2	225	30	87	263	152	42
3	207	31	85	269	36	58
4	146	20	86	509	14	97
Totals	746	89	88	1,166	247	79

[1] Percentage of inflow retained on field.

Furrow Cutback Irrigation

The effects of furrow cutback irrigation on water and sediment losses from a cooperator's potato field were evaluated in 1975. This study was conducted on a 1.7-hectare field which was 146 m long and had a slope of 1.0 percent. The field was divided into two equal plots and irrigated so that each plot received 12 uncontrolled or non-cutback irrigations and 12 controlled or cutback irrigations. Seasonal water and sediment budgets for the two plots are presented in Table 12.

The net application of water to the non-cutback set was 634 mm while that to the cutback set was 948 mm. The estimated seasonal consumptive use by the crop was 546 mm. The average application efficiencies for the non-cutback and cutback sets were 43 and 80 percent respectively. The non-cutback irrigations resulted in 853 mm of runoff and a net sediment loss of 92,540 kg/ha, while the cutback irrigations resulted in 241 mm of runoff and a net sediment loss of 12,294 kg/ha. These results re-emphasize the direct relation between irrigation efficiency and sediment loss. In this study, a 20 percent decrease in the total amount of water applied to a gravity-irrigated field resulted in an 85 percent decrease in the amount of sediment lost from the field.

TABLE 12

Seasonal Water and Sediment Budgets for Cutback and Non-Cutback Irrigations of a Potato Field, 1975

	Cutback Irrigations	*Non-Cutback Irrigations*
Inflow (mm)	1,189	1,487
Outflow (mm)	241	853
Application Efficiency (%)[1]	80	43
Sediment On (kg/ha)	2,014	2,201
Sediment Off (kg/ha)	14,309	94,741
Net Sediment Loss (kg/ha)	12,295	92,540

[1] **Percentage of inflow retained on field.**

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Economic Analysis of On-Farm Methods for Controlling Sediment and Nutrient Losses

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ABSTRACT

Information from 150 farmers in the Boise and Magic Valley areas was collected relative to current crop production, tillage and irrigation practices, cost of production, and income from crop production. The physical and economic data were processed by a budget generating method allowing standardized procedures of estimating costs of operating machinery and equipment. Partial budgets for each important crop grown in the two areas were developed from the computer program. Representative farms were simulated for the two areas based on the partial budgets. The simulated farm sizes will be a measure of the profitability of the present farming operation under existing water management practices.

The effects on farm net income of implementing erosion control practices on the farms, as well as by district, are analyzed using linear programming models. The analysis is based on two farm sizes in each area, and measures the effects on net farm income for a given set of rotation with increasing sedimentation loss, or alternately, a changing cropping pattern with a given lower limit of sediment loss with the resulting change in farm net income.

In measuring the external diseconomies effected by irrigation, an attempt was made to first determine the physical changes and then measure the economic cost. The physical impacts of irrigation were found to focus about water quality (sedimentation, specific conductivity, phosphorous, and nitrogen) and higher groundwater levels. Sedimentation resulted in annual costs of about $1.4 million in 1975 to the farm community to keep irrigation canals and ditches clean. High groundwater levels prevented the use of land for certain purposes (basements in houses) and actually cost the city of Meridian about $150 per month in pumping costs. Water quality in the Boise River (Boise compared to Notus) changed considerably due to economic activity in the valley. During the irrigation season, specific conductivity, nitrogen and phosphorous levels were five to ten times greater below the irrigated area. Boise River water also was found to contribute to pollution problems further downstream in the Snake River at Brownlee Reservoir.

INTRODUCTION

The full impact of erosion on surface irrigated land is becoming more and more widely perceived in society today. Not only is productive topsoil washed away over time, it is filling in downstream waterways and reservoirs and degrading the water quality of downstream flows. Many people are concerned over what can be done to reduce the magnitude of this problem, and what the costs would be.

This report is a first approximation of cost effectiveness estimates for selected methods of reducing the sediment loss from farms. It draws on data from three field monitoring studies and a survey of farmers in the Magic Valley and Boise Valley of southern Idaho in order to evaluate sediment loss control practices in terms of the cost effectiveness one could reasonably expect on an actual farm.

DATA SOURCES

A farm cost survey was conducted after the harvest season in 1975. One hundred and fifty randomly selected farm operators were interviewed and asked to describe their present farming practices, with special emphassis on field operations and irrigation practices. The

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study areas that were sampled were delineated so that the farms within them had soils, topography, and water supply conditions similar to those at the monitored field sites.

The information from the farm survey was processed so that representative farm models could be constructed for each study area. In this procedure, fifteen of the interviews were excluded because most of the farm was located outside of the study area, or had such sandy soils that it should not have been included in the study areas. Typical tillage, cultural and irrigation practices were then combined with input and commodity prices, and cost-and-return budgets were developed for representative farm models.

The physical parameters of irrigation water supply, return flow, and sediment loss were estimated for typical crop and field conditions in the study areas. These estimates were based on data from field monitoring projects conducted by the University of Idaho over the past five years (1, 2, 3). Data from sediment loss control investigations associated with these projects were summarized to estimate the physical effectiveness that can be reasonably expected from each practice.

ESTIMATION OF PHYSICAL PARAMETERS

There are so many variables that influence sediment loss from surface irrigated fields that it has been essentially impossible to predict how much soil will be lost from a particular field during the irrigation season. The figures presented in Table 1 are crude estimates of sediment loss on a typical farm in the areas studied. In this case, the concept of typical includes the assumptions of silt loam soils with slopes varying from one-half to four percent and current management practices.

TABLE 1

"Typical" sediment loss levels for surface irrigation crops on farms in the Magic Valley and Boise Valley.

Crops	*Typical Sediment Loss kg/ha*
Corn, beans, beets	*8,070*
Potatoes	*40,340*
Small grain, peas	*3,140*
Alfalfa	*900*

In order to estimate the cost effectiveness of alternative methods of sediment loss reduction, it was first necessary to estimate the physical effectiveness of these practices. The effectiveness of the methods analyzed in this paper was based on field work that has already been reported to this conference (2). Estimates were made of the expected sediment loss reduction for each practice under typical farm conditions. These estimates are presented in Table 2, in terms of the percentage of "typical" sediment loss that would be retained on the farm by using a particlar practice.

The sediment loss reduction practices are described briefly below.

Flow cut-back involves running the usual amount of water down the furrow or corrugate for the first six to eight hours of a set, or until the water is through to the lower end of the field, then cutting back stream size for the remainder of the set. This reduced flow results in less erosion and less soil transport in the furrows, however, more labor is required to perform the cut-back operation. It was assumed that the irrigation labor requirement was doubled by this practice because, in essence, the water must be set and then re-set.

TABLE 2

Expected sediment loss reduction for selected control practices on typical irrigated farms in the Magic Valley and Boise Valley.

Control Practice	*Percent of "Typical" Sediment Loss Retained on Farm*
Flow cut-back	30
Grass or grain strip	50
Sediment pond	67
Mini-basin	90
Sprinklers	100

To illustrate the effectiveness of the practice, assume that the sediment loss from a bean field is 8070 kg/ha under current management. Referring to Table 2, if a cut-back procedure was adopted, sediment loss from the field would be reduced by 30 percent, to 5649 kg/ha.

A grass or grain strip can be drilled in across the lower end of a row crop field to slow the velocity of tailwater running off the field during irrigation, which will cause it to deposit some of its sediment. Crops that are normally planted with a drill can be double (or even triple) planted in a strip across the lower end.

A sediment pond is a pond dug into a waterway for the purpose of reducing flow velocity and retaining sediment. The effectiveness of such a pond depends on its shape and size and on the volume of flow. In several monitored ponds, about two-thirds of the sediment entering these ponds over the irrigation season was retained by the pond.

The mini-basins are small shallow ponds constructed on the lower end of a field by putting in a low berm along the bank of the drain ditch. Other berms are constructed perpendicular to the drain ditch, so that each basin retains the tailwater flow of just a few furrows. The berm along the drain ditch also serves as a spillway when necessary, so it should be seeded with grass to minimize erosion into the ditch.

Sprinklers are in use in many areas of the West, mainly in areas that do not have facilities for surface irrigation or that have sandy soils that are difficult to surface irrigate. Some land is being converted to sprinkler irrigation using power-move systems, largely for the sake of labor saving and field consolidation. In addition, it is usually fairly easy to calibrate sprinkler systems so that the water application rate is equal to the soil intake rate. This makes more efficient use of irrigation water than most surface application methods and allows tailwater runoff (and sediment loss) from fields to be reduced to zero.

ECONOMIC ANALYSIS

The assumptions and calculations involved in figuring the cost effectiveness of the selected sediment loss control practices are described in the following sections.

Cut Back Flow

The irrigation labor that is typically involved in growing a crop was computed on the basis of the farm survey data. For each crop the median number of irrigations were multiplied by 1.0 hour/ha/irrigation to arrive at a figure for the hours of irrigation labor used per hectare over the irrigation season. This time does not include pre-season ditch work on the farm, which was computed separately for the crop budget.

The cut-back procedure was assumed to double irrigation, labor time, which was valued at $3.00 per hour. Table 3 presents the cost figures. For purposes of comparison, the cost per ton of sediment retained on the field is computed on the basis of both a 30 percent and an 80 percent retention of sediment that would be lost under typical present management. Field trials have shown a large variability in this sediment retention ratio — from 16 percent to slightly more than 85 percent (2).

Grass or Grain Strip

For row crops, a grass or grain strip at the end of a field would probably entail putting some land out of production. In order to estimate how much land would be out of production, it was necessary to make some assumptions regarding field size and shape. From the farm survey data, and from air photos in the Canyon Area Soil Survey for the Boise Valley, it was noted that the majority of fields in the study area were 4.05 ha or 8.10 ha tracts. The 8.1 ha fields were usually rectangular, with dimensions of 201 meters by 402 meters. Water may run across either the long or short headland, depending on field slope. For the sake of standardization, it was assumed that all fields are 8.1 ha and that the low headland averages 300 meters in length. If the seeded strip is 2.44 meters wide then 732 m^2, or 0.0732 ha of headland would be out of production.

It was further assumed that, for row crops, the headlands are less productive per unit area than the entire field — that headlands out of production would have yielded 80 percent of the field average used in the crop budgets. For corrugated crops, it was assumed that a normal harvest would be taken from the overplanted strip. No overplant procedure was used with alfalfa since an alfalfa field is one big vegetative strip.

Table 4 shows the costs of putting row crop land out of production for the vegetative strip, based on opportunity cost, or the value of production given up. Calculations are not done for potatoes. A vegetative strip would probably be obliterated by the first irrigation on potatoes. The operating costs consist of the costs associated with drilling in the strip at the beginning of the growing season and spreading the deposited sediment back over the field after harvest. For row crops, the "hassle factor" involved in getting the drill set up to plant the strip, driving to the field, planting the strip, driving back to the farmstead and putting the drill away is difficult to estimate. For calcula-

TABLE 3

Costs Associated With Flow Cut-Back to Reduce Sediment Loss on a "Typical" Farm in the Magic Valley or Boise Valley

Crop	No. of Irrigations	Irrigation Labor Normal (hr./ha.)	Irrigation Labor Cut-Back (hr./ha.)	Added Labor Cost ($/ha.)	Sediment Retained 30 percent Retention (t./ha.)	Sediment Retained 80 percent Retention (t./ha.)	Cost Per Ton of Sediment Retained 30 percent Retention ($/t.)	Cost Per Ton of Sediment Retained 80 percent Retention ($/t.)
Dry Beans	7	7	14	42.00	2.42	6.45	17.36	6.51
Bean Seed	8	8	16	48.00	2.42	6.45	19.83	7.44
Corn	7	7	14	42.00	2.42	6.45	17.36	6.51
Sugar Beets	10	10	20	60.00	2.42	6.45	24.79	9.30
Potatoes	12	12	24	72.00	12.10	32.27	5.95	2.23
Pea Seed	5	5	10	30.00	0.94	2.51	31.91	11.95
Win. Wheat	5	5	10	30.00	0.94	2.51	31.91	11.95
Spr. Grain	4	4	8	24.00	0.94	2.51	25.53	9.56
Alfalfa Hay	6	6	12	36.00	0.27	0.72	133.33	50.00

NOTE: "t." is the abbreviation for "metric ton" or "tonne" (1000 kg.).

TABLE 4

Net Returns and Opportunity Cost of Land Out of Production For Vegetative Strips (Average For Farm Models).

Crop	Net Return to Land And Management Field Average ($/ha)	Net Return to Land And Management Headlands (20% Lower Yield) ($/ha)	Opportunity Cost of 0.0732 ha out of Production $
Dry Beans	529	334	24.45
Bean Seed	988	688	50.36
Corn Seed	806	477	34.92
Sugar Beets	875	504	36.90

tion of labor cost and machinery variable costs, the actual field time was multiplied by four in an attempt to include all the steps in the operation.

TABLE 5

Annual Operating Costs Associated with Vegetative Strips on 8.1-Hectare Fields.

Row Crops			
Machine variable costs for drill and tractor:			$
$3.88/hr. X 0.86 hr./ha. X 0.0732 ha. X 4	=		0.98
Labor cost of seeding:			
$3.00/hr. X 0.86 hr./ha. X 0.0732 ha. X 4	=		0.76
Wheat or barley seed:			
100 kg./ha. X 0.0732 ha. X $0.24/kg.	=		1.76
Dirt Spreading:			
$3.70/ha. X 8.1 ha.	=		29.97
			33.47
Corrugated Crops			
		Grain	*Peas*
Machine variable costs for drill and tractor:		$	$
$3.88/hr. X 0.86 hr./ha. X 0.0732 ha.	=	0.24	0.24
Labor cost of seeding:			
$3.00/hr. X 0.86 hr./ha. X 0.0732 ha.	=	0.19	0.19
Seed-Wheat or Barley		1.76	
Peas			16.00
Dirt Spreading:			
$3.70/ha. X 8.1 ha. X .05	=	14.98	14.98
Total Annual Operating Costs		17.17	31.41

TABLE 6

Total Annual Costs Associated with Vegetative Strips on 8.1-Hectare Fields.

Crop	Opportunity Cost Of Land Out of Production $	Total Costs Operating Costs $	Total Costs Whole Field $	Per Hectare $	Sediment Retained (t./ha.)	Cost per Tonne of Sediment Retained ($/t.)
Dry Beans	24.45	33.47	57.92	7.15	4.03	1.77
Bean Seed	50.36	33.47	83.83	10.35	4.03	2.57
Corn Seed	34.92	33.47	68.39	8.44	4.03	2.10
Sugar Beets	36.90	33.47	70.37	8.69	4.03	2.16
Pea Seed	0	31.41	31.41	3.88	1.57	2.47
Grain	0	17.17	17.17	2.12	1.57	1.35

For grain and pea fields, only the time involved in making another pass over the lower end of the field was used in computing costs.

Machine field time and variable costs per hour of operation are from the model farm budgets for grain enterprises. It was assumed the farmer already has the machinery and that machinery fixed costs had already been allocated to crop enterprises. Therefore, no fixed costs were charged to the strips. Table 5 shows the calculation of operating costs for row crops, grain and peas. Total annual costs for vegetative strips are shown in Table 6.

Dirt spreading was accomplished by an extra time over the field with a land plane. This would probably have to be done every year for row crops, every other year for grain and peas. Based on numbers computed for the cost budgets, this operation would cost $3.70 per hectare.

Sediment Ponds

The cost effectiveness of sediment ponds was analyzed for a situation where each 8.1 hectare field would have a pond in its tailwater drains. Pond size and excavation costs depend on the volume of sediment to be handled. Table 7 shows the figures used for planning purposes in this study.

Dirt spreading costs are usually about equivalent to excavation cost, so excavation

TABLE 7

Sediment Pond Size and Excavation Cost Estimates for Surface Irrigated Crops on 8.1-Hectare Fields.

	Pond Size			
Crop	*Area (m^2)*	*Volume (m^3)*	*Excavation Cost (@ \$0.75/m^3) (\$)*	*Percent of Pond Filled in One Year*
Beans, Beets	54.9	65.9	49.41	50
Corn Seed	54.9	65.9	49.41	50
Potatoes	168.4	252.5	189.40	100
Grain, Peas	36.6	43.9	32.94	30
Alfalfa, Hay	36.6	43.9	32.94	8

TABLE 8

Annual Operating Costs for Sediment Ponds, with Surface Irrigated Crops on 8.1-Hectare Fields.

Crop	*Excavation and Spreading Costs-Pond Full \$*	*Percent of Pond Filled in One Year*	*Annual Operating Costs \$*
Beans, Beets	98.82	50	49.41
Corn Seed	98.82	50	49.41
Potatoes	378.80	100	378.80
Grain, Peas	65.88	30	19.76
Alfalfa Hay	65.88	8	5.27

TABLE 9

Opportunity Cost of Land Out of Production for Sediment Ponds on 8.1-Hectare Fields.

Crop	*Net Return Given Up (\$/ha.)*	*Land Area (ha.)*	*Opportunity Cost of Land Out of Production \$*
Dry Beans	334	0.016	5.34
Bean Seed	688	0.016	11.01
Corn Seed	477	0.016	7.63
Sugar Beets	504	0.016	8.06
Potatoes	714	0.051	36.41
Pea Seed	592	0.011	7.61
Winter Wheat	381	0.011	4.19
Spring Wheat	331	0.011	3.64
Spring Barley	111	0.011	1.22
Alfalfa Hay	257	0.011	2.83

TABLE 10

Total Annual Costs Associated With Sediment Ponds on 8.1-Hectare Fields.

			Total Costs			
Crop	*Opportunity Cost of Land Out of Production \$*	*Operating Costs \$*	*Whole Field \$*	*Per Hectare \$*	*Sediment Retained (t./ha.)*	*Cost per Tonne of Sediment Retained (\$/t.)*
Dry Beans	5.34	49.41	54.75	6.76	5.41	1.25
Bean Seed	11.01	49.41	60.42	7.46	5.41	1.38
Corn Seed	7.63	49.41	57.04	7.04	5.41	1.30
Sugar Beets	8.06	49.41	57.47	7.10	5.41	1.31
Potatoes	36.41	378.80	415.21	51.26	27.03	1.90
Pea Seed	7.61	19.76	27.37	3.38	2.10	1.61
Winter Wheat	4.19	19.76	23.95	2.96	2.10	1.41
Spring Wheat	3.64	19.76	23.40	2.89	2.10	1.38
Spring Barley	1.22	19.76	20.98	2.59	2.10	1.23
Alfalfa Hay	2.83	5.27	8.10	1.00	0.60	1.67

costs were doubled to arrive at the total operating costs for sediment ponds. Table 8 presents these operating costs on an annual basis.

To compute the costs associated with putting land out of production by the installation of a sediment pond, the surface area of the pond was tripled to allow for margins around it. This area was then multiplied by the value of output given up on a headland area of that size. Once again, row crop yields on headlands were assumed to be 20 percent below field average. Table 9 shows the opportunity costs of the land out of production, and Table 10 presents total annual costs for the sediment ponds.

Mini-Basins

The land area out of production for mini-basins would be the same as for vegetative strips, so the opportunity cost of land out of production would also be the same. It was assumed that the basin along the drain ditch bank would have to be shaped and seeded every five years. Costs for this operation on a headland 300 meters long would be as follows:

Labor: 5 hr. x $3.00/hr. ÷ 5 years =	$3.00/year
Machine variable costs for tractor, "V" ditcher and blade: 2.5 hr. x $2.00 hr. ÷ 5 years =	$1.00/year
Grass seed: **(area seeded - 300 m. x 0.8 m = 240 m^2** **240 m^2 ÷ 61.5 m^2/kg. of seed = 4.0 kg.** **4.0 kg. x $2.20/kg ÷ 5 years**	**$1.76/year**
	$5.76/year

Maintaining the mini-basins would involve spreading dirt and rebuilding the field berms every year on row crops, every other year on grain and peas. For alfalfa, basins put in before establishment would serve for the duration of the stand. Construction costs are shown in Table 11.

The amount of dirt to be spread, relative to a vegetative strip, would be proportional to the effectiveness of the two methods. The basins retain 1.8 times as much sediment as would a vegetative strip for a given field and crop, so spreading costs were figured to be 1.8 times as much. The details of dirt spreading costs are

TABLE 12

Dirt Spreading Costs for Mini-Basins on 8.1-Hectare Fields.

Crop	*Cost* $
Beans, Beets, Corn	53.95
Potatoes	74.92
Grain, Peas	26.96
Alfalfa Hay	7.74

TABLE 11

Basin Construction Costs for Mini-Basins on 8.1-Hectare Fields.

Crop	*Furrow Spacing (m)*	*No. of Furrows Per Basin*	*No. of Basins on 300 m. Headland*	*Machine Labor Time @ 0.1 hr./Basin*	*Shovel Work @ 0.2 hr./Basin*
				(hr.)	(hr.)
Beans, Beets	1.12	4	67	6.7	13.4
Corn	0.76	4	99	9.9	19.8
Potatoes	0.91	4	82	8.2	16.5
Grain, Peas Alfalfa Hay	0.76	6	66	6.6	13.2

	Machine Labor Cost @ $3.00 hr.	*Shovel Work @ $3.00/hr.*	*Machine Variable Costs @ $2.00 hr.*	*Total Berm Const. Costs Per Time*	*Total Berm Const. Costs Annual*
	$	$	$		
Beans, Beets	20.10	40.20	13.40	73.70	73.70
Corn	29.70	59.40	19.80	108.90	108.90
Potatoes	24.60	49.20	16.40	90.20	90.20
Grain, Peas	19.80	39.60	13.20	72.60	36.30
Alfalfa Hay	19.80	39.60	13.20	72.60	(72.60 ÷ yrs. of stand)

shown in Table 12. Table 13 shows the total annual costs for the mini-basins. Operating costs are the sum of 15.76 plus total basin construction costs on an annual basis (from Table 11), plus dirt spreading costs (from Table 12.)

Sprinkler Irrigation

Any large scale conversion of surface irrigated lands to sprinklers would have many impacts that are beyond the scope of this paper. The availability of power for pumping would probably be a major constraint. Even so, it might be useful to look at the costs of installing and operating a sprinkler system for comparison with other methods of reducing sediment loss. A sprinkler system is to be operated so as to eliminate water runoff and sediment loss from most fields.

Cost estimates were computed for a side-roll sprinkler system, as shown in Table 14. The system consists of a pump taking water out of a pond, a mainline and six laterals for 56.7 hectares of irrigated crops on a quarter section of land. Depreciation was calculated on a straight-line basis, with a useful life of 15 years for all components and a salvage value of 10 percent of new price. Annual interest was computed at eight percent per year on average investment, which is defined by the formula:

Average Investment =
(New Price + Salvage Value)÷ 2.

Costs for power and repairs are shown on a per irrigation basis in Table 14, as are irrigation labor savings. In Table 15, the total (net) costs of owning and operating the sprinkler system is presented by crop. The cost of sediment retention is also presented in Table 15.

SUMMARY OF RESULTS

The sediment loss reduction practices considered in this paper show a wide variation in costs.

Relative cost effectiveness depends on the crops under consideration, their present level of sediment loss and the physical effectiveness of the control practice. The costs per ton of sediment retained on the farm are shown for each practice in Table 16.

Flow cut-back is the most expensive way to retain a given volume of sediment if sediment loss is only reduced by 30 percent. With an 80 percent reduction, flow cut-back is still a more expensive way to retain soil than mini-basins for all crops except potatoes.

For all crops, sediment ponds can retain about two-thirds of normal sediment loss at a cost of less than two dollars per tonne. On grain crops, a vegetated strip, or lower end overplant, compares favorably with sediment ponds on a cost per unit basis. However, the strips retain less total sediment. Costs per ton of sediment retained range from $1.77 to $2.57 for the vegetative strips under row crops.

TABLE 13

Total Annual Costs Associated With Mini-Basins on 8.1-Hectare Fields.

			Total Costs			
Crop	*Opportunity of Land Out of Production* **$**	*Operating Costs* **$**	*Whole Field* **$**	*Per Hectare* **$**	*Sediment Retained (t./ha.)*	*Cost Per Tonne of Sediment Retained ($/t.)*
Dry Beans	24.45	133.46	157.86	19.49	7.26	2.68
Bean Seed	50.36	133.41	183.77	22.69	7.26	3.13
Corn Seed	34.92	168.61	203.53	25.13	7.26	3.46
Sugar Beets	36.90	133.41	170.31	21.03	7.26	2.90
Potatoes	52.26	170.88	223.14	27.55	10.09[1]	2.73
Pea Seed	50.65	69.02	119.67	14.77	2.82	5.24
Win. Wheat	27.89	69.02	96.91	11.96	2.82	4.24
Spr. Wheat	24.23	69.02	93.25	11.51	2.82	4.08
Spr. Barley	8.13	69.02	77.15	9.52	2.82	3.38
Alfalfa Hay (2 yr. stand)	18.81	37.70	56.51	6.98	0.81	8.62

[1] Because of the large volume of sediment, the mini-basins on a potato field would probably fill up before the season ended. For purposes of comparison, it is assumed that 25% of incoming sediment for the season will be retained.

Mini-basins retain a greater proportion of normal sediment loss than do strips or ponds, but are also more expensive, both in total and on a per unit of sediment basis.

Converting the surface irrigation system to side-roll sprinkler could eliminate sediment loss from the farm, but involves a large jump in costs from those associated with surface tailwater management practices. Again, potatoes are an exception, because of the huge volume of sediment loss under the surface irrigation practices that were assumed to be typical. For other crops, the conversion to sprinklers would cost about 10 times as much per unit of sediment retained as would sediment ponds and five times as much as the mini-basins. On grain, sprinklers would cost 18 times as much as ponds and six times as much as mini-basins, per unit of sediment retained.

TABLE 14

Annual Costs of Owning and Operating a Side-Roll Sprinkler System on 56.7 Hectares of Irrigated Crops.

Item	*Investment Cost ($)*	*Annual Depreciation ($/yr.)*	*Annual Interest ($/yr.)*
Laterals	27,000	1,620	1,188
Mainline	6,600	396	290
50 HP. Pump	3,500	210	154
Pond	500	33	20
	34,600	2,259	1,652

Costs Per Hectare:

Depreciation and Interest:	$69.00
Power:	3.70 per irrigation
Repairs:	2.50 per irrigation
Labor Cost Savings:	
Ditch Maintenance:	9.25
Irrigation:	0.75 per irrigation

TABLE 15

Costs of Owning and Operating a Side-Roll Sprinkler System, Relative to Sediment Retention.

Crop	*No. of Irrigations*	*Power Cost ($/ha.)*	*Repair Cost ($/ha.)*	*Labor Cost Savings Ditch Maint. ($/ha.)*	*Labor Cost Savings Irrigation ($/ha.)*	*Depr. and Interest ($/ha.)*	*Net Annual Cost ($/ha.)*	*Sediment Retained (t./ha.)*	*Cost of Sediment Retained ($/t.)*
Dry Beans	7	25.90	17.50	-9.25	-5.25	69.00	97.90	8.07	12.13
Bean Seed	8	29.60	20.00	-9.25	-6.00	69.00	103.35	8.07	12.81
Corn Seed	7	25.90	17.50	-9.25	-5.25	69.00	97.90	8.07	12.13
Sugar Beets	10	37.00	25.00	-9.25	-7.50	69.00	114.25	8.07	14.16
Potatoes	12	44.40	30.00	-9.25	-9.00	69.00	125.15	40.34	3.10
Peas	5	18.50	12.50	-9.25	-3.75	69.00	87.00	3.14	27.70
Win. Wheat	5	18.50	12.50	-9.25	-3.75	69.00	87.00	3.14	27.70
Spr. Grain	4	14.80	10.00	-9.25	-3.00	69.00	81.55	3.14	25.97
Alfalfa Hay	6	22.20	15.00	-9.25	-4.50	69.00	92.45	0.90	102.72

TABLE 16

Cost Effectiveness Summary for Selected Sediment Loss Control Practices.

	Cost Per Ton of Sediment Retained					
Crop	*Vegetative Strip*	*Sediment Ponds*	*Mini-Basins*	*Flow Cut-Back 30% Retention*	*Flow Cut-Back 80 Retention*	*Side-Roll Sprinkler*
Dry Beans	$1.77	$1.25	$2.68	$ 17.36	$ 6.51	$ 12.13
Bean Seed	2.57	1.38	3.13	19.83	7.44	12.81
Corn Seed	2.10	1.30	3.46	17.36	6.51	12.13
Sugar Beets	2.16	1.31	2.90	24.79	9.30	14.16
Potatoes	—	1.90	2.73	5.95	2.23	3.10
Pea Seed	2.47	1.61	5.24	31.91	11.95	27.70
Win. Wheat	1.35	1.41	4.24	31.91	11.95	27.70
Spr. Wheat	1.35	1.38	4.08	25.53	9.56	25.97
Spr. Barley	1.35	1.23	3.38	25.53	9.56	25.97
Alfalfa	—	1.67	8.62	133.33	50.00	102.72

Work is presently going forward to incorporate these cost data into linear programming models of representative, or model, farms for each study area. The results of this work will describe how a farm manager would meet a specified limit on sediment loss from his farm. It will also show how this adaptation will affect farm income.

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Combining Agricultural Improvements and Desalting of Return Flows to Optimize Local Salinity Control Policies

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ABSTRACT

Mathematical simulations of the cost-effectiveness relationship for various agricultural and desalination alternatives for controlling salinity in irrigation return flows are being developed. The question of respective feasibility for each type of control is determined through minimizing the total costs, thereby optimally selecting the best measures to implement. To demonstrate the concept, desalting and canal linings were compared for the Grand Valley in western Colorado. Results indicate that desalting exhibits superior feasibility to linings of canals where seepage rates are low. In general, desalting will exhibit its best feasibility when applied to large-scale applications and when salt pickup rates stemming from irrigation return flows are small.

INTRODUCTION

The development of desalination technology in the United States has been guided by the basic objective outlined by Congress to the U.S. Department of the Interior's Office of Saline Water (now combined with the Office of Water Resources Research to form a single department entitled, "Office of Water Research and Technology"). This objective is:

> "to provide for the development of practicable low-cost means for producing from sea water or from other saline waters (brackish and other mineralized or chemically charged waters), water of a quality suitable for agriculture, industrial, municipal, and other beneficial consumptive uses."

To satisfy this objective, Congress has provided funding for a massive research and development effort, although the application to large scale systems is only now beginning to occur. The traditional scope of saline water conversion programs has been to reclaim otherwise unsuitable waters for specific needs. However, the scope has dealt almost exclusively with utilization of product water directly rather than returning it to receiving waters in order to improve the overall resource quality. Thus, with mounting concerns for managing salinity on a regional or basin-wide scale, the potential for applying desalination within the framework of an overall salinity control strategy is an interesting one. In fact, the use of desalting systems to resolve critical salinity problems is already being planned as part of the Colorado River International Salinity Control Project agreement between the United States and the Republic of Mexico (U.S. Department of the Interior, 1973).

In the context of regional salinity control, desalting costs can be expressed in dollars per unit volume of salt extracted in the brine discharge, rather than the conventional index of costs per unit volume of reclaimed product water. In this manner the respective feasibility of desalination and other alternatives for salinity management can be systematically compared during the process of developing strategies for actual implementation of salinity controls. This paper examines the use of desalination in controlling the quality of irrigation return flows in conjunction with the more traditional approaches associated with maximizing irrigation efficiency.

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DESALINATION COSTS

In general, the costs associated with desalting systems may be either classified as those expended during construction or those required annually to operate and maintain the facilities. These costs are subject to inflational pressures and must therefore be periodically updated. Once costs are current, various relationships between the costs and system performance can be formulated. A detailed description of desalting costing models was given by Walker (1976) based upon work reported by Prehn, et al. (1970) and U.S. Department of the Interior (1972).

Capital and Annual Costs

It might be noted that the capital costs delineated by Walker (1976) are based on estimating functions current during mid-1971 and therefore must be updated to prevailing price levels. The costs for construction, steam supply, and general site development can be estimated in the present time frame by employing the Engineering News Record Construction Cost Index (Engineering News Record is published monthly by McGraw-Hill, Inc.). In July of 1971 the ENR index was 952, whereas in January 1976 it had risen to 1354. Consequently, an early 1976 cost estimate would be 1354/952 or 1.42 times the 1971 functional estimate. Other capital costs for interest during construciton, owners' general expense, start-up, and working capital are functions of construction, steam, and site development costs and are therefore updated automatically. Land costs may be estimated on a current basis by utilizing existing land prices.

Estimates of capital costs for feedwater and brine facilities require several other inflational factors. For example, conveyance pipeline costs are modified by the Bureau of Reclamation Concrete Pipeline Cost Index, CPI (1.17 for July 1971 and 1.88 for January 1976). Others are the USBR Pumping Plant Cost Index, PPI (1.26 for July 1971 and 1.98 for January 1976). USBR Pumps and Prime Mover Cost Index, PMI (1.41 in July 1971 and 2.13 in January 1976), and the USBR Canal and Earthwork Cost Index, EI (1.27 in July 1971 and 1.92 in January 1976).

The annualization of the construction costs is divided according to whether or not the costs represent depreciating capital. Depreciating capital cost are multiplied by a "fixed charge factor", FCR, which is the percentage of total depreciating capital cost that is encompassed by interest, amortization, insurance, and taxes. Non-depreciating capital costs are multiplied by the prevailing interest rate selected for project evaluation or incurred in borrowing.

Annual costs must also be updated for price increases due to inflation. Labor and materials and steam generation O & M are updated using the Bureau of Labor Statistics Labor Cost Indices, SIC494-7, which was 3.76 in July 1971 and 4.93 in January 1976. Chemical costs are multiplied by the present to 1971 ratio of the Bureau of Labor Statistics Cost Index for chemicals and allied products (181 for 1976, #104.4 for 1971). Fuel and electricity costs are estimated using present prices for these inputs and are therefore always estimated currently. Replacement costs are expressed as functions of plant capacity and are thus not updated by cost indexing.

Water and Salt Costs

After describing the individual costs associated with desalting systems, it is generally necessary to express such cost in either dollars per unit volume of product water (for water supply feasibility) or dollars per unit of salt extracted (for salinity control studies). These cost bases are determined in this study by dividing the total annual costs by the annual volume of product water or brine salts.

Depreciating capital costs for the plant itself and the feedwater — brine disposal systems are multiplied by the fixed charge factor. Non-depreciating costs are next multiplied by the interest rate, added to the annualized depreciating costs, and finally summed with the remaining annual costs; thus, using the eight capital cost categories and six annual cost elements described by Walker (1976) gives:

$$C_{pw} = \frac{FCR \sum_{i=1}^{6} C'_i + I_r \sum_{i=7}^{8} C'_i + \sum_{i=9}^{14} C'_i}{C_p + U_f \times 3.65 \times 10^{-4}} \qquad (1)$$

for product water costs, and for salt costs:

$$C_s = \frac{FCR \sum_{i=1}^{6} C'_i + I_r \sum_{i=7}^{8} C'_i + \sum_{i=9}^{14} C'_i}{C_b \times C_{bo} \times U_f\, 3.65 \times 10^{-4}} \qquad (2)$$

in which,

C_{pw} = unit cost of product water, $\$/m^3$;
C_s = unit cost of brine salts, $\$/\text{metric ton}$;
C_i = total annual cost for element i, $\$/\text{year}$ (feedwater + plant + brine)

C'_1 = construction cost;
C'_2 = steam generation;
C'_3 = site development;
C'_4 = interest during construction;
C'_5 = start-up costs;
C'_6 = owner's general expense;
C'_7 = land;
C'_8 = working capital;
C'_9 = labor and materials (operational);
C'_{10} = chemicals;
C'_{11} = fuel;
C'_{12} = electrical;
C'_{13} = steam generation O & M; and
C'_{14} = replacement.

C_p = product water volume, m^3/day;
C_b = brine volume, m^3/day;
C_{bo} = TDS concentration in brine, mg/l;
FCR = fixed charge rate;
I_r = interest rate; and
U_f = use factor — fraction of total time in actual operation.

Available Processes

Saline water conversion processes involve the use of a semi-permeable barrier, which excludes either water or salt flow. The barrier may be a membrane which excludes salt such as reverse osmosis (RO); one which excludes water such as electrodialysis(ED); or one that exchanges salt for hydrogen and hydroxide ions which unite to produce water (ion exchange, IX). The barrier may also be a "phase boundary" which excludes the salts. For example, vaporization of water using multi-stage flash (MSF), vertical tube evaporation-MSF (VTE-MSF) and vapor compression-VTE-MSF (VC-VTE-MSF) leaves the salts in the remaining solution as does solidification of water using vacuum-freezing-vapor compression (VF-VC) processes (Probstein, 1973).The driving potential for each of these processes is either heat (distillation and freezing), pressure (RO), electrical (ED), or chemical (IX).

Each desalination process has specific advantages depending on such factors as feedwater chemistry and desired product water. A general review of these factors along with a description of the costing model for each technology is too lengthy for this paper, so the interested reader is referred to the original references.

Sensitivity in Cost Estimates

The application of desalting technology to regional water quality management tends to be a very site specific problem. As a result, generalization of cost analyses is difficult. However, it might be useful to point out the model's sensitivity to various input parameters relative to an arbitrary "base" so the relative importance of the variables can be reviewed. Table 1 summarizes the base values of some typical input parameters that might be found in an irrigation return flow problem.

Desalting System Capacity

Desalting costs expressed in terms of dollars per ton of salt removed, or dollars per cubic meter of product water, exhibit substantial economies of scale. For the base condition, the scale effects for each process are illustrated in Figure 1 (ion exchange has not been included because of high TDS in the feedwater). In nearly every process, the unit costs at 950 m^3/day are 2-4 times the cost at 121,000 m^3/day. The CTE-MSF, VC-VTE-MSF, and RO process costs at the lower value are 3.5 to 3.6 times the upper capacity indicating much larger importance of scale that is associated with MSF (2.80), VF-VC (2.78), or ED (2.13). Of these specific processes, electrodialysis is more affected by input parameters and therefore should be evaluated more closely in the reconnaissance investigation.

The scale factor in desalination will generally preclude small installations for salinity control since other measures for reducing salinity will be cheaper. However, as the level of implementation increases and the marginal costs of desalting decrease, this technology may become highly competetive with the various other alternatives. Consequently, a major parameter in a salinity control analysis that can be expected to affect the potential use of desalination is the level of implementation.

TABLE 1

Standardized desalting model input parameters for variable sensitivity analyses.

C_p = 1.5 x 10^4 m^3/day (4mgd)
TDS_i = 5000 mg/l
TDS_p = 5000 mg/l
ENR = 1354
BLS_1 = 4.93
BLS_2 = 181
CPI = 1.88
PPI = 1.98
PMI = 2.13
EI = 1.92
D_b = 1000 m (3280 feet)
D_f = 100 m (328 feet)
D_{ib} = 100 m (328 feet)
D_{if} = 1000 m (3280 feet)
E = 1.07 (3.5 feet)
E_c = \$7.2 x 10^4/M Joules (\$20/100 kwh)
FCR = 0.0856
F_r = \$1.20 x 10^3/M Joules (\$1.14/MBTU)
I_r = 7%
L_p = \$4,942/ha (\$2000/acre)
T = 15.6°C (60°F)
U_f = 0.90
Na = 1260 mg/l
Mg = 123 mg/l
Ca = 393 mg/l
K = 8 mg/l
HCO_3 = 106 mg/l
Cl = 2035 mg/l
SO_4 = 1075 mg/l
NO_3 = 0 mg/l

Feedwater is supplied by wells and brine is disposed of with injection wells.

Feedwater Salinity

Because of referencing desalting costs to salinity control, the feedwater salinity is an important parameter in the evaluation of the alternative processes. The distillation and freezing methods are not substantially limited by input salinity since the same measures are necessary to desalt 1000 mg/l feedwater as for 10,000 mg/l. Consequently, the higher the feedwater salinity the lower the unit cost for these processes. Reverse osmosis and electrodialysis, on the other hand, use membranes to effect a salt removal and therefore are directly affected by feedwater salinity. Calculations were made at the base input condition with various levels of input salinity to evaluate this factor. The results are plotted in Figure 2, where the assumption is made that individual ionic species do not create limiting conditions.

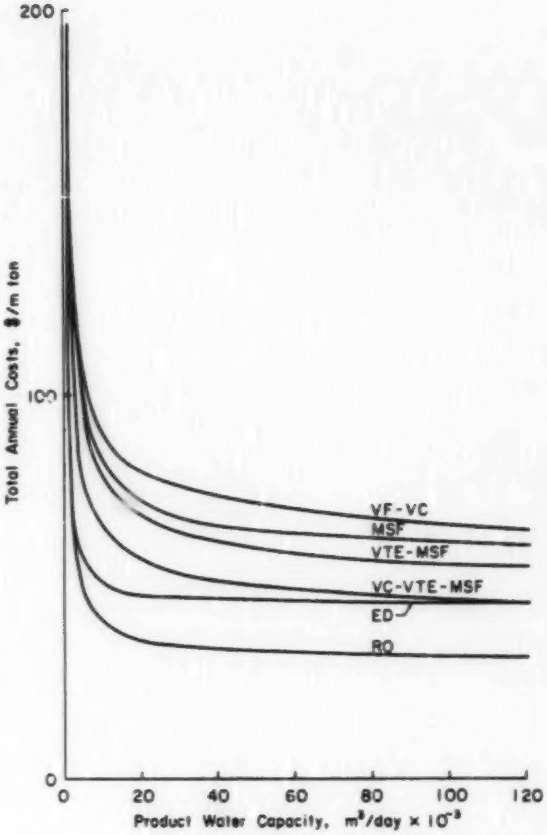

Figure 1. Illustration of desalting costs as functions of desalting capacity for the base condition.

In all the methods simulated in the costing model (except electrodialysis) the costs at 2000 mg/l would be double those at 5000 mg/l and five times that at 13,000 mg/l. However, the rate of change of the salinity versus cost ratio diminished toward increasing salinity values. The electrodialysis process is significantly less affected by feedwater salinity mainly because of its modular construction and the direct relationship between power consumption and salinity.

Operation and Maintenance

Unlike the fairly predictable construction cost items, operation and maintenance costs are subject to year to year inflational pressures which cannot always be effectively predicted. At the base condition, the O & M costs were typically somewhat more than 50% of the total annual costs, as shown below.

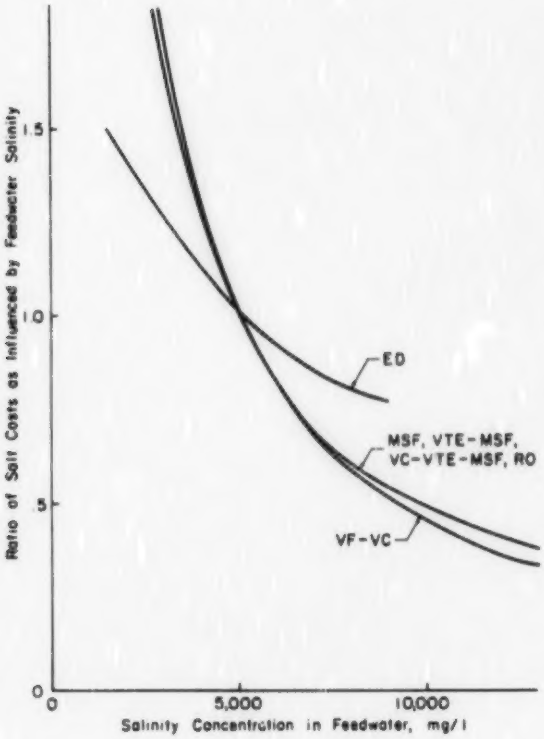

Figure 2. Effect of feedwater salinity on desalting costs.

Process	*Percent of Total Annual Cost Attributable to O & M*
MSF	60%
VTE-MSF	57
VC-VTE-MSF	46
ED	58
RO	56
VF-VC	56

It is interesting to evaluate the effects of interest rate on the relative importance of operation and maintenance costs. For example, if the interest rate was increased from 7% at the base to 10.5%, O & M costs decline from more than 50% to 39%, or about 11% in most cases. In terms of total costs, this 50% increase in interest rates increased unit costs by a low of 21.5% for MSF processes to 28.6% for VC-VTE-MSF systems. In each case studied, the effects of scale on feedwater salinity did not affect the percentages given above with the exception of electrodialysis. In the ED analysis, the effects of plant capacity produced O & M precentages ranging from 58% to 66% as the capacity increased from the base to 121,000 m^3/day.

Specific items in the operating expense categories are also of interest to water quality management planning. For instance, electrical and fuel costs accounted for the following percentages of total annual costs:

Process	*Cost of Electrical Power*	*Cost of Fuel*
MSF	9.8%	32.0%
VTE-MSF	5.4%	33.4%
VC-VTE-MSF	2.1%	24.0%
ED	27.5%	0 %
RO	20.4%	0 %
VF-VC	32.8%	0 %

Rate increases for both electricity and fuel produce proportional increases in annual costs. For example, in a MSF system if electricity rates increase 50%, annual costs will increase (0.50) (0.98) = 0.049, or 4.9%. These data illustrate the importance of electrical costs for membrane and freezing processes and fuel for distillation methods of desalination.

Land

Because land area for desalting systems is a non-depreciating capital costs and can therefore be amortized indefinitely, land costs for the base condition ($5,000/ha) account for only 1-8% of total annual desalting costs as shown below.

Process	*Land Costs as a Fraction of Total Annual Costs*
MSF	3.8%
VTE-MSF	3.9%
VC-VTE-MSF	4.8%
ED	5.8%
RO	7.7%
VF-VC	0.7%

Feedwater and Brine Facilities

Of the factors involved in evaluating desalting feasibility, the feedwater and brine disposal facilities may be the most site-specific variables. In the reference situation using feedwater wells 100 m deep and 1000 m from the plant, and brine injection wells 100 m deep and 100 m from the plant, and brine injection wells

1000 m deep and 100 m from the plant, the costs were as follows:

Process	*Percentage of Total Annual Costs Attributable to Feedwater and Brine Disposal Facilities*
MSF	21%
VTE-MSF	21%
VC-VTE-MSF	25%
ED	30%
RO	40%
VF-VC	12%

Differences in the values reflect different volumes of feedwater, brine, and overall costs.

The choice of a feedwater or brine disposal system is very important in evaluating these alternatives. Feedwater wells, for example, can account for about 15% of the costs of feedwater and brine disposal systems. Likewise, the choice of brine injection wells over evaporation ponds can be a significant decision. In the base example, evaporation ponds would cost about 70% more than injection wells for each alternative except VF-VD in which case they would cost approximately 7% less. Thus the solution and location of this equipment should be considered and optimized for each potential location.

Technical Advances

The desalting submodel does not include compensation for technological improvements in equipment or processes that are almost certain to appear. The potential user of this work should therefore be cognizant that substantial errors can be introduced if updating with current literature is not part of using this desalting submodel.

AGRICULTURAL SALINITY CONTROL COSTS

Improved management and structural rehabilitation are often regarded as the most feasible treatments of an irrigation system to improve the quality of return flow. Indirect approaches such as limiting irrigation diversions, effluent standards, land use regulations, and economic incentives may also be considered although they appear more difficult to implement. Whenever salt pickup is the objective of salinity control, however, the specific control measures should impact segments of the irrigation system which contribute to the magnitude of local groundwater flow. This may be accomplished by reducing seepage from various elements of the conveyance system and minimizing deep percolation from over-irrigation. Return flow quality may also be improved by relief and interceptor drainage to collect subsurface flows before a chemical equilibrium is reached with the ambient soil or aquifer materials. The respective feasibility of individual measures depends on developing and evaluating cost-effectivenss functions for controlling each alternative input to the groundwater region where salt pickup is assumed to occur. These are based on soil and aquifer chemical behavior as interpreted by prerequisite analyses. Thus, the relationship between groundwater flow and salt loading can be determined in such a manner that control costs can be related to reductions in salt loading.

The mathematical development of the agricultural salinity control cost-effectiveness functions is too lengthy for this presentation. Since canal and ditch linings are among the more popular salinity control measures and demonstrate the pertinent concepts, the following discussion will be limited to this salinity control alternative.

Water Conveyance Linings

The contribution to local or regional salinity problems from irrigation water conveyance networks may be the result of a number of factors. First, unlined channels allow seepage into underlying soils and aquifers where naturally occurring salts might be dissolved and transported into receiving waters. Second, the structural and managerial condition of a system may support large areas of open water surfaces or phreatophytes which concentrate salinity in return flows (through evaporation and transpiration). Finally, the operation of the system may preclude efficient water utilization by the individual irrigator, especially if deliveries are not made in accordance with crop demands. The costs to remedy these problems are generally limited to those associated with lining and rehabilitation of the waterway. However, so far as improved management may be required, some costs associated with educational programs and legal/administrative adjustments may be incurred.

To test the feasibility of conveyance system improvements relative to other salinity control measures, the mathematical model developed in the following paragraphs will center on one principal channel improvement alternative;

concrete lined systems. It is assumed that this alternative along with supportive structures represent the generally applicable technology in therms of both utilization and cost.

Seepage from canal, lateral, and ditch conveyance networks may be reduced or eliminated by lining the perimeter with an impervious material such as concrete, plastic, asphalt, or compacted earth to note several of the more common methods. Concrete is probably the most commonly employed lining material because of the combined advantages of cost, ease of construction, availability, reduced maintenance, and low permeability. The costs of concrete linings (either slip-form or gunite) vary with local economic and topographic conditions, channel geometry and size, and requirements for miscellaneous water management, safety, and environmental structures. For specific locations it is important to prepare cost estimates on a case by case basis, although for planning purposes it is useful to have generalized expressions.

A review of concrete lining costs by Walker (1976) indicated that such costs could be reasonably well estimated as a function of wetted perimeter and updated to present and future conditions with an appropriate cost index. A simpler methodology based on design discharge can also be utilized, and will be variable in this model.

Data presented by U. S. Department of the Interior (1963, 1975) and Evans, et al. (1976) were evaluated by the following general relationship:

$$U_c = K_1 \, Q^{K_2} \qquad (3)$$

where,

U_c = unit lining cost, \$/m;
Q = design discharge, m³/sec; and
K_1, K_2 = regression coefficients.

After transforming the data with the Bureau of Reclamation canal and earthwork cost index to a base time of 1975, the K_1 and K_2 values were 29.70 and 0.56, respectively. It should be noted, however, that even in the same locale these unit costs vary substantially. Equation 3, therefore, is intended only as a general estimating formula. The unit costs in Equation 3 include only the earthwork, relocation, and lining costs and do not include costs for fencing, diversion structures, safety structures, etc. The latter costs are also highly variable depending upon the many site-specific conditions. An examination of such costs as given by the U.S. Department of the Interior (1975) showed a range of \$12/m to \$50/m with a average of \$22/m. Unless otherwise specified, the average figure will be used in this analysis. Consequently, the construction cost may be written in 1975 dollars:

$$C_c = 29.70Q^{0.56} + 22 \qquad (4)$$

In addition to the construction costs, one must consider service facilities, engineering, investigations, and other adminstrative expenses. The Bureau of Reclamation uses a 35% factor for these costs, so Equation 4 can be written as a total cal cost:

$$C_c = 40.1Q^{0.56} + 29.70 \qquad (5)$$

where,

C_c = 1975 value of concrete canal linings in \$/m.

In order to calculate the total costs for a given length of canal, ditch, or lateral, Equation 5 must be integrated over the applicable limits. Because water is continually being withdrawn from a conveyance channel, both wetted perimeter and discharge decline along the length of the channel. The distribution of these parameters may be estimated in a number of ways if measurements are not available. For instance, a linear decline can be assumed, or the decrease can be formulated in terms of acreage distributions. Assuming a linear decrease, the wetted perimeter at a specific location can be determined by:

$$WP = WP_m \, (1\text{-}bL/L_t) \qquad (6)$$

in which,

WP_m = the wetted perimeter at the channel inlet, m;
L = length from inlet to specified point, m;
L_t = total length of channel, m; and
b = empirical constant representing the fraction of maximum wetted perimeter remaining at end of the channel.

and similarly for the design discharge:

$$Q = Q_m \, (1\text{-}bL/L_t) \qquad (7)$$

where,

Q_m = inlet channel capacity in m³/sec.

Combining Equations 5 and 7, yields,

$$C_c = 40.1 \times Q_m^{0.56} \, (1\text{-}bL/L_t)^{0.56} + 29.70 \qquad (8)$$

Then, the total capital costs for lining L meters of channel, $\bar{C}_c$, are determined by integrating Equation 8 as it varies from 0 to L meters:

$$\bar{C}_c = 40.1xQ_m^{0.56}\frac{L_t}{1.56b}(1-(1-bL/L_t)^{1.56}) + 29.7L \quad (9)$$

Equation 9 assumed that the lining proceeds in the downstream direction, however, the choice of either upstream or downstream lining direction depends on their relative cost-effectiveness. To determine this choice, it is first necessary to define the salinity control effectiveness resulting from a particular lining project. Only the salt loading effects will be considered in the model at this stage of development. If a salt pickup condition exists, the equilibrium salinity in return flow will differ from the salinity in the seepage water so that after accounting for phreatophyte withdrawals,

$$\Delta S_1 = \Delta S_c V_s \frac{Q_g - Q_p}{Q_g} 10^{-6} \quad (10)$$

where,

ΔS_1 = reduction in salt loading due to the linings, metric tons/m annually;

ΔS_c = difference between the equilibrium salinity concentration in the return flows and the salt concentrations in the seepage seepage waters, mg/l;

Q_g = total groundwater addition, m^3/year;

Q_p = phreatophyte use of groundwater, m^3/year; and

V_s = total volume of seepage, m^3/year, as determined by:

$$V_s = N_d \ \Delta SR \ WP' \quad (11)$$

in which,

N_d = number of days per year seepage occurs;

WP' = wetter perimeter of original channel m; and

ΔSR = change in seepage rate affected by lining, m^3/m^2/day.

It might be pointed out that the ΔSR value might also be written as a length distributed parameter in this model if measurements or other data are available.

Substitution of Equation 6 into Equation 10 leads to an expression than can be integrated over the length of the lining to determine the total salinity control. This expression for the downstream lining case is:

$$S_c = \Delta S_c \frac{Q_g - Q_p}{Q_g} 10^{-6} N_d \ \Delta SR \ WP'_m \frac{L_t}{2b}(1-(1-bL/L_t)^2) \quad (12)$$

This question of lining direction can be addressed by approximating the marginal costs at both ends and then comparing the results. First, let K_1, K_2, and K_3 be defined respectively as:

$$K_1 = 40.1 \ Q_m^{0.56} \quad (13)$$

$$K_2 = S_c N_d \ \Delta SR \frac{Q_g - Q_p}{Q_g} WP'_m \ 10^{-6} \quad (14)$$

$$K_3 = 29.7 \quad (15)$$

Then the marginal cost estimate would be found by dividing Equation 9 by Equation 8;

$$MC = \frac{K_1 (1-bL/L_t)^{0.56} + K_3}{K_2 (1-bL/L_t)} \quad (16)$$

in which,

MC = marginal lining cost estimate, \$/ton.

At the inlet where L=0, the marginal cost estimate, MC_i is:

$$MC_i = \frac{K_1 + K_3}{K_2} \quad (17)$$

whereas at the end where $L=L_t$, the marginal cost estimate MC_u, is:

$$MC_u = \frac{K_1 (1-b)^{0.56} + K_3}{K_2 (1-b)} \quad (18)$$

Subtracting Equation 18 from 19 and simplifying gives:

$$MC_i - MC_u = \frac{K_1}{K_3}\left(1 - \frac{1}{(1-b)^{0.44}}\right) + \frac{K_3}{K_2}\left(1 - \frac{1}{(1-b)}\right) \quad (19)$$

Under the assumptions of this model, Equation 19 is always negative, leading to the conclusion that lining should always proceed downstream. Consequently, the cost-effectiveness functions for concrete linings is determined from Equations 9 and 12 by solving for the independent variable L in Equation 12 and substituting the resulting expression into Equation 9. The resulting cost-effectiveness function is:

$$\bar{C}_c = K_1' + \frac{K_3 L_t}{b} - K_1'\left(1 - \frac{S_c}{K_2'}\right)^{0.78} - \frac{K_3' L_t}{b}\left(1 - \frac{S_c}{K_2'}\right)^{0.5} \qquad (20)$$

in which,

$$K_1' = \frac{K_1 L_t}{1.56b} \qquad (21)$$

$$K_2' = \frac{K_2' L_t}{2b} \qquad (22)$$

COMPARISON OF TECHNOLOGIES

The preceeding paragraphs demonstrate the complexity of determining optimal irrigation return flow quality controls. These problems of complexity can be significantly alleviated by "staging" the calculations (also known as multi-level optimization). This procedure can take several forms, but its additive format is the easiest to understand. From the array of agricultural alternatives, the optimum set is determined as a function of control level. The same is determined for the desalting alternatives. And finally, agricultural and desalting cost-effectiveness functions are combined to produce the optimal overall strategy. To demonstrate these concepts, desalting will be compared to canal lining for the conditions in Grand Valley. Since the Grand Valley situation is a case study in these proceedings, the description of local hydro-salinity systems will be omitted from this paper.

Optimal Canal Lining Strategies

There are fourteen major canal and ditch systems in the Grand Valley ranging in length from 74 kilometers for the Government Highline Canal (17 m^3/sec capacity) to 4 kilometers for the Mesa County Ditch (1 m^3/sec capacity). The pertinent parameters for each canal, along with the seepage contribution to salt loading, were determined for use in Equation 20. The resulting functions were then minimized using the Jacobian Differential Algorithm developed by Walker, et al. (1973) for a range of possible salinity reductions desired from a canal lining program. These results are given in Figures 3 and 4. Figure 3 shows the total capital constructions costs as a function of the annual salt load reduction to be realized. The upper curve is the minimum cost associated with each value on the abscissa. Underneath the upper curve are the costs attributed to the various valley wide canals. For example, if the contribution of canal seepage to the salt loading problem was to be reduced by 87,500 tons annually through linings, the capital construction cost would be approximately \$27 million with \$13.5 million on the Government Highline canal, \$8.7 million on the Grand Valley system, \$2.2 million on the small ditches (e.g., Price, Stub, etc.), \$1.6 million on the Orchard Mesa System, and the remainder on the Redlands system. Figure 4 illustrates how much of the respective canal systems would be lined under this minimum cost policy.

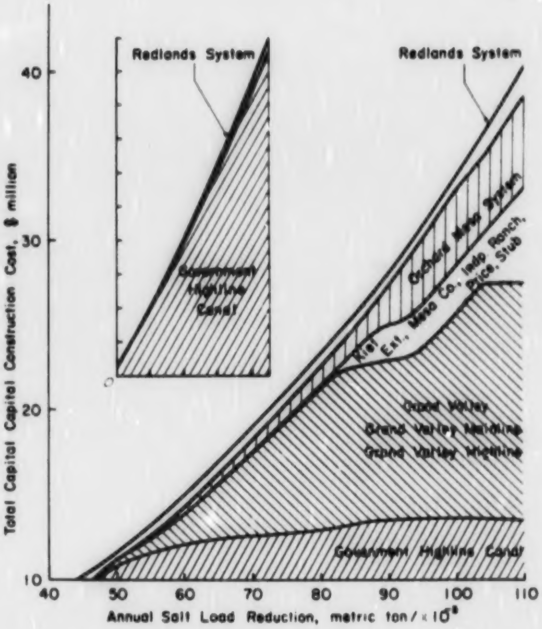

Figure 3. Optimal canal lining strategy in the Grand Valley of western Colorado.

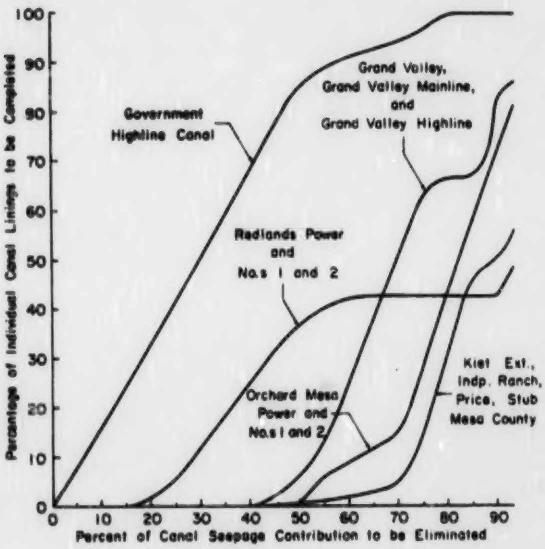

Figure 4. Canal lining implementation strategy for the Grand Valley example.

The results obtained in optimizing canal lining policies is interesting in the sense that they demonstrate the need to initiate linings on more than one segment of the conveyance system when full scale implementation begins. The cost savings in implementing according to a minimum cost strategy amount to about 30% in this case (Walker, 1976).

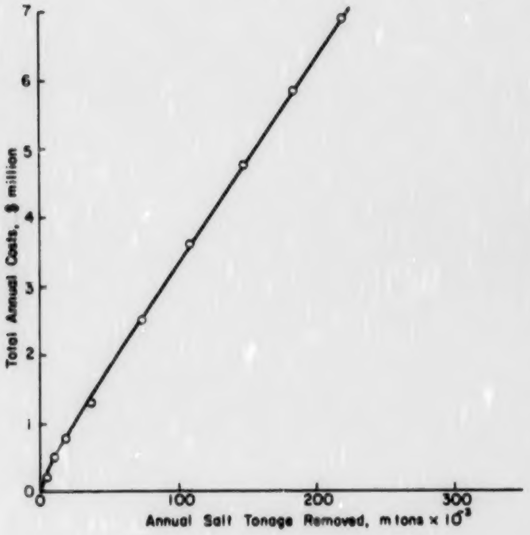

Figure 5. Cost-effectiveness of desalting in Grand Valley.

Desalting Policy

Desalting evaluations involve, first, determining the most effective process and, second, the best feedwater-brine facilities. In the Grand Valley situation, reverse osmosis is clearly the most advantageous. A summary of desalting costs as a function of salt load removal is given in Figure 5.

It might be noted that whereas agricultural salinity control costs (at least for canal and ditch linings) exhibit increasing marginal costs with scale, the reverse is true for desalting technologies. Consequently, early improvements (or ones of small scale) favor agricultural improvements while larger operations enhance the feasibility of desalination.

Combined Agricultural-Desalting Methodologies

The respective feasibility of agricultural and desalting methods is determined by optimizing the individual contributions from each aggregated analysis. In the example of canal lining and desalting by reverse osmosis, this would imply combining Figures 3 and 5 in an optimal manner.

The optimal canal lining-desalting strategy for the Grand Valley is given in Figure 6 for seven values of interest rates. (During the analysis, the parameter having the largest single influence on the respective feasibility was interest rates for project evaluation). Interest rates, of course, are not the only important factor. For example, Figure 7 was prepared using canal lining costs 50% higher than computed. It is obvious the desalting would be employed more in a plan utilizing these results, but the reverse would be true if desalting cost estimates turned out to be conservative.

SUMMARY AND CONCLUSIONS

An attempt has been made in this paper to evaluate the possible role of desalination technology in controlling the quality of irrigation return flows. The Grand Valley in western Colorado has been utilized to demonstrate the concepts proposed herein, but the space available for this paper prohibited an examination beyond simply evaluating the respective feasibility of canal lining and desalting. The results are indicative of the need to develop optimizational modeling analyses as part of salinity control planning on both a local and regional scale.

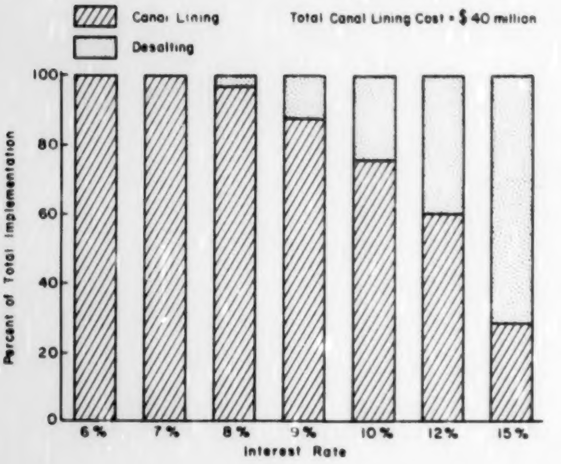

Figure 6. Comparison of canal lining and desalting in reducing salt loading from the Grand Valley.

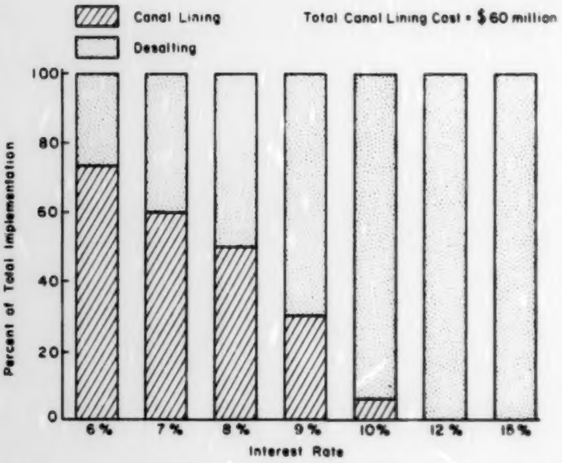

Figure 7. Comparison of desalting and canal lining salinity control alternatives assuming 50% increase in lining costs.

Desalting is a viable alternative to lining canals, laterals, and head ditches. Its relative feasibility cannot be ascertained generally, but must be evaluated case by case. However, in the areas where salt pickup rates are high, desalting will enjoy its most favorable advantage even though desalting is likely to be implemented after a substantial investment in agricultural improvements.

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Irrigation Return Flow Models

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Practical Applications of Irrigation Return Flow Quality Models to Large Acreages

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ABSTRACT

Numerous return flow quality simulation models have been developed in recent years. Practical use of these tools on large irrigation projects is discussed in terms of study objectives, data requirements and availability, model detail and sensitivity, inherent limitations, and reliability and interpretation of results. The modeling efforts of the Bureau of Reclamation and other institutions are used to illustrate the utility and practicability of these new tools. Potential and present model users should gain valuable insight into the benefits and pitfalls of return flow quality modeling.

INTRODUCTION

There has been a proliferation of irrigation return flow simulation models in recent years in terms of both basic development (e.g., 5, 6, 8) and practical application (e.g., 6, 10, 11) to real world problems. These models range from simple conceptual formulations to complex programs requiring a large digital computer. Although a wide variety of techniques and models are generally available to water resource management and development agencies, consultants, environmental organizations and others, they sometimes fail to utilize the most appropriate procedures. A rapidly advancing technology together with a general lack of any real guidelines for approach/model selection and useage are among the causes. The situation is compounded by the lack of a centralized source of return flow model codes and documentatation. As a result, studies are often completed and management decisions made with less than optimal useage of available tools.

This paper attempts to present a realistic approach to prediction studies involving irrigation return flow quality and quantity, particularly from large areas. Return flows include surface and subsurface components such as surface runoff, operational losses, seepage from water conveyance systems, and subsurface drain returns. Quality parameters can include concentrations of major cations and anions, total dissolved solids, pesticides, nitrates, phosphates, trace elements, dissolved oxygen, BOD, temperature, etc. Suggestions are included for needed improvements in dissemination of information on models and modeling techniques. Following the suggested study approach will better enable water resource agencies and others to make decisions involving irrigation return flows.

Basic Approach

Studies involving predictions of irrigation return flow qualities and quantities should follow an approach which allows efficient utilization of available tools and techniques, but still affords a suitable feedback mechanism for making needed changes during the study. Feedback is a vital consideration due to the many uncertainties present at the beginning of any irrigation return flow (IRF) study.

From the outset, a specific objective should be identified and a study plan established which states what is to be accomplished and determines the resources necessary to complete the study. Far too many IRF studies are started without any clear idea of what is to be done, what resources are needed, and how the information will be used. Although the study plan

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may be altered as the work progresses, an initial plan is required to provide a starting place.

The three essential or key elements of any good return flow study plan are illustrated in Figure 1. These include the available models and approaches, the data requirements and availability, and sensitivity analyses. To be functional, the key elements must interact with each other and with the original objective. Many problems associated with IRF studies can be traced to absent or unreasonable objectives, failure to consider one or more of the key elements, or failure to initiate and maintain an effective feedback mechanism.

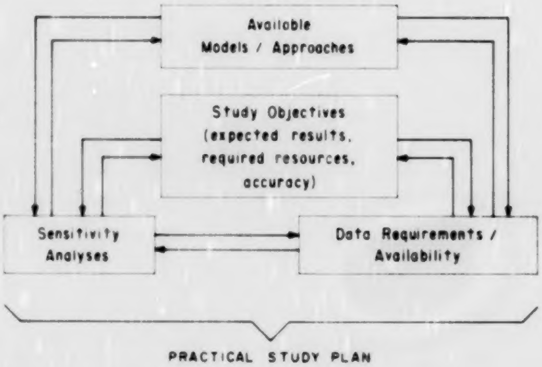

Figure 1. Study Plan Analysis

A practical study plan should evolve from a realistic objective which has considered the key elements, which in turn have been interacted with each other.

Available Approaches/Models

A wide range of techniques and models are currently available for use in IRF studies. As illustrated in Figure 2, the practitioner working in the field tends to favor models or approaches with the least amount of technical detail. Conversely, theorists generally prefer models which contain many micro-details. The applied modeler who is (or should be) looking for the simplest model or approach that does the job, often finds himself between these two extreme viewpoints. This position, as shown by the solid line in Figure 2, is the most likely to produce a practical model which still considers the important variables. Depending on the particular application, the detail of the model or approach used could fall within a wide range. The real task lies in selecting the appropriate technique or model from the available spectrum.

Actual model selection should begin with the study objective and progress via the interactive or feedback process shown in Figure 1. A thorough knowledge of the general field conditions and the types and scope of available tools is essential. Field personnel with site specific knowledge of the individual project area should be involved in the IRF study. Otherwise, it will be extremely difficult to know which approach or model to apply.

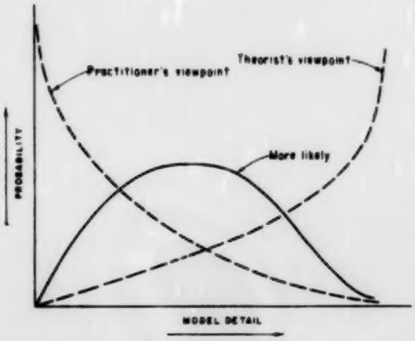

Figure 2. Probability of having the best model for a given application.

Available tools should be reviewed to determine the most appropriate model or technique. Unfortunately, only a handful of modelers in the United States and elsewhere are aware of the latest techniques available in this rapidly expanding field. These individuals have their own specific versions of IRF models. Field personnel (modelers) wanting to apply IRF techniques are usually forced to select an existing model or to resort to outdated techniques. It is extremely difficult for someone to readily adapt parts of various IRF models to individual needs due to the lack of a centralized location for source codes and documentation. Consideration should be given to establishing such a central library of IRF models or submodels. Another highly beneficial information source would be a comprehensive manual describing the methods and techniques for conducting irrigation return flow quality and quantity studies. No such manual currently exists, and the practitioner is forced to improvise based on in-house capabilities.

Various attempts have been made to group and classify IRF models. Designations such as stochastic and deterministic, dynamic and steadystate, conservative and nonconservative, analytic and numerical are all commonly used, and IRF models often incorporate several of them. All models have certain inherent limitations which affect the way they can be used. For example, a steady-state, conservative model would be extremely difficult to apply to a problem requiring dynamic projections of nonconservative variables. Likewise, many IRF models utilize representative sets of data defining initial soil and aquifer conditions. The model user cannot input continuous data, and is limited to and must interpret a few representative cases.

The study objective together with the particular field situation determine to a great extent the approach or model which can be used. If the objective is to get reconnaissance level estimates from an area with limited data, then a simple conceptual model or experience in similar areas may be the best approach. Conversely, long term monthly concentrations of nonconservative constituents in return flows from a project could require a dynamic, nonconservative numerical model.

In any event, selection of a suitable model or approach should consider the basic study objective, the field situation, variable sensitivities, and data requirements and availability. It could very well be necessary to alter the model or approach during the study as feedback becomes available.

Sensitivity Analyses

The sensitivity analysis has been included as an essential element of any IRF study plan. Models or approaches are sometimes used which fail to properly consider the significant variables, while other variables are handled with too much detail. Every aspect of a study can benefit from a sensitivity analysis. The model/approach used, the data requirements, and the basic objective itself can hinge on the results of such an analysis.

In some cases, the entire study may be centered around the sensitivity aspects. A determination of output variability as a function of variability in the inputs could provide sufficient information to make management decisions.

It should be pointed out, however, that sensitivity studies can be overdone and abused. Since the true future variability and interactions of the input parameters are seldom known, any attempt to use sensitivity analyses to draw boundaries or zones of uncertainty around predicted results should be viewed with caution. Nevertheless, sensitivity analyses should be an important part of the study plan.

A relative error diagram similar to that shown in Figure 3 can be used to compare the sensitivities of several input variables. Many variables will plot similar to variables 1 and 2 in the figure. That is, predicted results are not found to be highly sensitive to any one input parameter. Variables with slopes much greater than var. 4 would require special attention. In an actual application, the effects of many variables tend to cancel each other giving an overall attenuated effect similar to the composite.

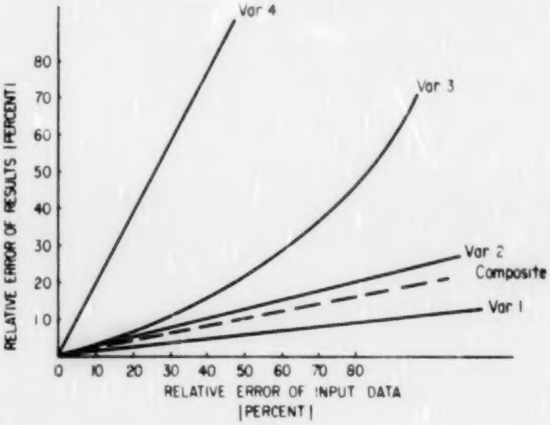

Figure 3. Variable Sensitivity

Data Requirements/Availability

Data collection programs on large projects all suffer from the same problem; there are never enough resources to do high density sampling on the entire project. The data requirements of various models/approaches must be considered in light of the availability of data. Indeed, the basic objective of the study must often be tempered to reflect the available data.

The relationship between data requirements and availability is shown in Figure 4. Generally, models must be selected which are between the extremes.

Many IRF models utilize a number of individual data sets which represent conditions found in the project area. An effort should be made to minimize the number of data sets and computer runs. One possibility is to establish basic mapping units within the project and more intensely study a representative portion of each unit. It is often possible to correlate individual parameters with certain key parameters so that extensive sampling and analytical procedures are unnecessary for each sampling location.

In all cases, the costs of data collection programs should be weighed against the penalties (costs) of not collecting data (see Figure 5). For example, the risk of downstream pollution could outweigh the cost of collecting more data from the project. In any event, data monitoring programs should be extended beyond the time of the initial IRF studies to further verify the projections and to allow for any remedial actions which might be necessary.

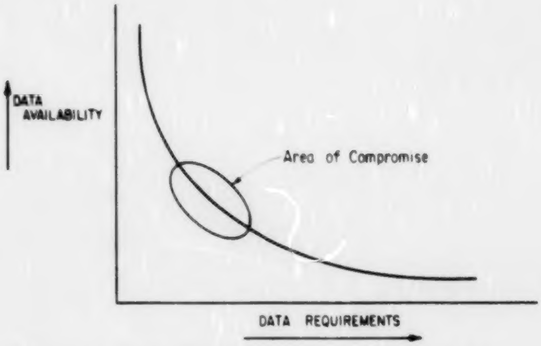

Figure 4. Data Requirements and Availability

Interpretation of Results

The manner in which the results of an IRF study are interpreted sometimes causes considerable confusion. A hypothetical time plot of total dissolved solids (TDS) concentrations in a stream below an irrigation project is shown in Figure 6. Depending on which parts of the plot are examined, varying conclusions can be made about the impace of the project on the stream.

The "with project" curve indicates that the stream will never exceed a total dissolved solids concentration of 500 mg/liter which is equal to some state water quality standards for drinking water. However, during the maximum impact period, stream salinity is increased as much as four or five fold. At steady state, the salinity increase is only about 50 percent.

It should always be recognized that confidence bands surround both the projected and base curves in Figure 6. If these bands are too wide, the results become meaningless. While it is currently beyond the state-of-the-art to compute the location of say the 95 percent confidence bands on the predicted curve, research in this area could yield valuable results. The primary problem is the inability to predict future economic and social conditions which control certain inputs to the modeling process.

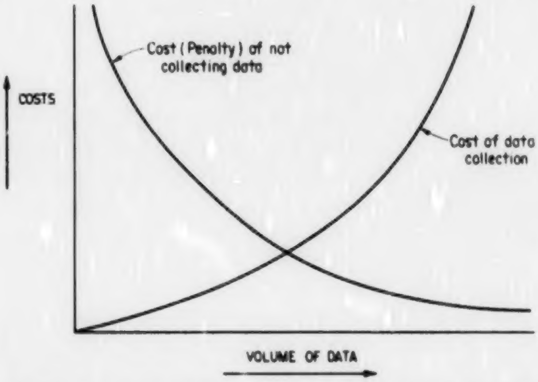

Figure 5. Cost of Data Collection (or lack thereof)

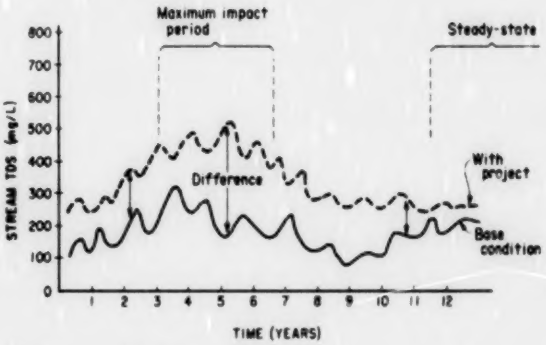

Figure 6. Model results

Further complications to Figure 6 occur when the receiving streams experience low flows or go dry periodically. In the Western United States, high total dissolved solids concentrations are associated with low flows. Although the mean or median concentrations may be increased by irrigation return flows, maximum concentrations are often reduced. The question of whether a project will cause adverse impacts downstream is always difficult to answer. All factors must be examined in a rational manner.

Whenever long term results of an IRF study are presented, the entire picture should be given including the base conditions, the maximum impact period, and steady state. Even with short term projections, the base curve should be presented along with the predicted values.

Common Problems in IRF Studies

Studies involving irrigation return flow quantities and qualities are often complex and involve several scientific and engineering disciplines. Most organizational difficulties with IRF studies arise because the efforts are not properly coordinated, and sufficient time and resources are not committed to the complex task. Table 1 lists some of the more common mistakes often made in IRF studies. Most of these could be avoided if an approach such as the one suggested in this paper was followed.

The proper attitude towards IRF studies, particularly those dealing with large areas, is essential to a successful study. The underlying purpose usually is (or should be) to obtain additional information which can be used to help make a management decision. Results with very high accuracy levels generally are not possible nor are they necessary in most cases.

Strong Points of Current IRF Study Techniques

Computer simulation models are finding increased useage in IRF studies. While problems still exist, such as lack of extensive verification and "oversell" of computer predictions, the techniques represent a major advancement in IRF technology. It is now possible to simultaneously consider many of the important variables which affect return flow qualities and quantities. Previous "desk top" techniques, while valid within the context of thier assumptions and limitations, could not hope to handle the complex interactions now being simulated.

In addition to pure computing power, simulation modeling forces the practicing scientist and engineer to look at the overall system rather than extrapolate from his often narrow area of expertise. This means that other disciplines are more likely to be included in the study. An interdisciplinary approach to the IRF study provides a forum for highly beneficial, although sometimes frustrating, exchanges between the respective fields.

A third benefit of simulation modeling stems from the modular nature of most IRF model computer codes. This allows (or should allow), subroutines developed for a particular subsystem to be used as part(s) of other models. Thus, for example, solutions to complex problems in soil chemistry can be used by soil physicists without need for detailed involvement in a less familiar area.

TABLE 1

Common Mistakes Made in IRF Studies

1. Setting objectives which are not obtainable within the confines of available resources (dollars, time, manpower, etc.)
2. Failure to allow sufficient time for the necessary feedback mechanisms to operate. (at least 3 times the single run through estimate should be allotted).
3. Conducting studies using great detail on insensitive parameters. Not knowing which parameters are really sensitive.
4. Data requirements exceed data availability; insufficient time allotted for data collection.
5. Use of the local approach or model without considering other possibilities.
6. Failure to consider or use feedback from on-going activities.
7. Adopting the viewpoint that results from computer simulation models are either all powerful or completely useless.
8. Overplay of results; failure to identify the weaknesses; over emphasis on data supporting a single viewpoint.
9. Empirical extrapolations based on years of experience rather than applying a sound scientific approach.
10. A modeling staff which is not qualified in certain aspects of the study.
11. Not knowing whether to use a long term, short term, or steady state approach. Over reliance on any one of these.
12. Crash programs to study irrigation return flow quality and quantity without adequate time for data collection and other study aspects.

IRF Model Applications

The use of irrigation return flow models to predict the quantity and quality of return flows from large areas or projects has become fairly common in recent years. The Bureau of Reclamation has been studying the long term impacts of its projects on the environment. Rather sophisticated computer simulation models (3, 4, 5, 9) are being used to assess the quantity and quality of irrigation return flows and the effects of these waters on receiving streams. Specific applications have included the Garrison Diversion Unit (11), the Oahe Unit (10) the Dolores, Animas-La Plata and San Miguel Projects, the San Juan Collector System, the Wellton-Mohawk Project (9), the Navajo Indian Irrigation Project, and the San Luis Drain.

The University of California at Davis has been involved in modeling irrigation return flows from large areas. Predictions have been made for the Glenn-Colusa Irrigation District and the Panoche Drainage District near Sacramento, California (6) and the Sutter Basin, California (7).

New Mexico Institute of Mining and Technology, Socorro, New Mexico, has studied irrigation return flows in the Mesilla Valley, New Mexico (2).

Utah State University has been involved in several IRF modeling studies on large acreages including the Bear River Basin (1, 8) and other areas (12).

SUMMARY AND CONCLUSIONS

Useful IRF models depend on past research, present technology and knowledge, and continuing assessments based on comparisons of predicted and observed responses of operational projects. Wise model use depends on a thorough understanding of the model capabilities and limitations. Successful application in turn depends on an adequate data base.

Data collection, basic research, model development, and model application are interdependent activities that require continuous feedback for maximum success. Thus basic research provides a conceptual framework for developing the model, the model aids in the design of a data collection program, and the data are used to apply the model to a given area. The results of this application may dictate additional research, modification of the model, and an expanded data collection program, Early activation of this feedback process will assure maximum usefulness of any IRF model.

IRF studies involve a broad spectrum of disciplines including researchers, data collectors, modelers, and decisionmakers representing such varied professions as geology, hydrology, soil science, agronomy, and hydraulics. A multidisciplinary approach is indicated which requires substantial effort to establish effective communications.

IRF studies often require large masses of data. Even though simple models are used, reliance on computers is natural. This in turn introduces computer associated problems that have nothing to do with irrigation return flows, including documentation and maintenance of source codes.

Development of a practical study plan is essential to a successful IRF study. It is based on the interaction of available models/approaches, data requirements/availability, and sensitivity analyses with the study objective and between themselves. The final product is a result of tradeoffs and compromises. Proper interpretation of results should then assure improved decisions regarding irrigation return flows.

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Areal Predictions of Soil Water Flux in the Unsaturated Zone

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ABSTRACT

Irrigation, salinity and potential ground or surface water pollutants are intimately related to water and solute movement in the soil profile. Ideally, soil water fluxes and water composition are managed in order to provide a desirable plant growing environment and/or acceptable quantities and qualities of drainage water. The problem of predicting or averaging such fluxes is very difficult due to the intrinsic variability of the soil's physical and chemical properties.

In this study, predictions of soil water flux are made accounting for the spatial variability of the soil water parameters. Calculations are made using field-measured distributions of conductivity and soil water tension — water content relationships for Panoche loam and Pima clay loam soils. In the first set of simulations a conductivity of the form $K = K_\circ \exp[\alpha(\theta - \theta_\circ)]$ *is utilized where* θ *is the volumetric water content and* $K_\circ$ *and* $\theta_\circ$ *the initial values of hydraulic conductivity and water content for the wetted profile. The* α *is an empirical constant for each site and depth. Monte Carlo simulations are used to find flux distributions with the simplified drainage equation* $J_L = K_\circ(1 + \alpha K_\circ t/l)^{-1}$. *The flux* J_L *is a random output dependent upon the stochastic nature of* $K_\circ$ *and* α *and is found to be approximately log-normal for all times studied.*

In the second set of calculations, flux distributions are found using the more cumbersome, finite difference solution to the nonlinear moisture flow equation. This allows inclusion of more realistic boundary conditions as well as plant water uptake.

The results are a step towards finding the most effective way of determining and expressing water flux as a function of time. Also, addressed are reliability of areal predictions and measurements.

Irrigation, salinity and the transport of water-carried constituents are intimately related to soil water flux in the unsaturated zone. As soil is heterogeneous by nature, the velocity varies from site to site within any specified area. The nature of the areal distribution is basic in order to describe either mean values or relative flow amounts occurring at adjacent points. In this paper, we will first review measured distribution patterns of water-related, soil physical parameters. Then, we will explore ramifications of such distributions with regard to water flux in the unsaturated zone.

OBSERVED DISTRIBUTION PATTERNS

Frequency distributions have been presented for a variety of water-related, soil parameters by Nielsen, Biggar and Erh (1973). Coelho (1974), Cassel and Bauer (1975), Biggar and Nielsen (1976), and Warrick, Mullen and Nielsen (1977a, 1977b). Other recently reported studies closely related include that by Keisling (1974), Carvallo et al. (1976), Baker and Bouma (1976) and Peck, Luxmoore and Stolzy (1977).

Results for water contents measured under ponded water conditions or for water retained at given tensions have been found to be approximately normally distributed in several cases. In Figure 1, results are shown from Coelho (1974) for water retained at fifteen bars, the value commonly chosen to correspond to the permanent wilting percentage. The data is for 500 sampling points each at a 50 cm depth and on a 4 m grid within a 76 x 96 m area of Pima clay loam. The data points are for a class interval of 0.6% water content gravimetrically. The distribution is approximately normal with a mean of 12.2 and a standard deviation of 2.0% water gravimetrically. Values of Coelho taken at 36 sites over the 87 hectares of the same Pima

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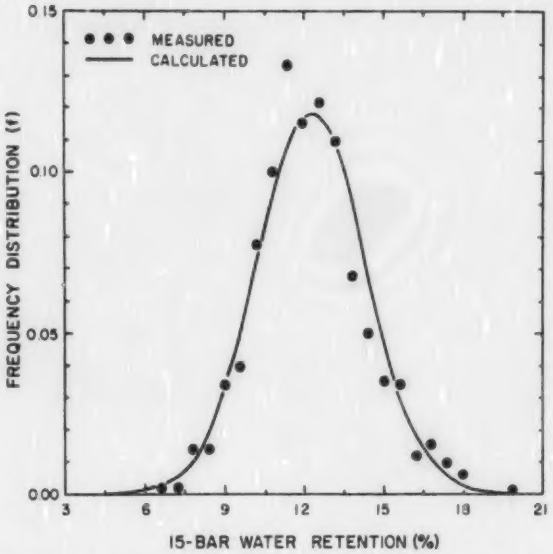

Figure 1. Frequency distribution for 500 measurements of 15-bar water retention (After Coelho, 1974).

clay loam also were approximately normal as was the bulk density and a porosity index factor. Cassel and Bauer (1975) also found approximately normal distributions for 15 bar moisture retention over a 1.3 hectare area of Maddock sand loam, but a tendency towards skewness for Beardon silty clay. Nielsen, Biggar and Erh (1973) observed volumetric water content distribution for infiltration under steady ponding to also be normal over 150 hectares of Panoche soil. Both of these last two studies found a near normal distribution for bulk density.

For several properties more directly related to flow velocities, skewed distributions seem to be more the rule than the exception. Figure 2 is a cumulative frequency diagram of the logarithm of the saturated conductivity $K_{sat.}$ by Coelho (1974) for the 87 hectare area of Pima clay loam. The straight line is for a log normal distribution which, of course, is highly skewed.

Nielsen et al. (1973) determined the unsaturated conductivity for each site of the form

$$K = K_0 \exp[\alpha(\theta - \theta_0)] \qquad [1]$$

where K_0 and θ_0 are values of the hydraulic conductivity and water content under steady ponded conditions (K_0 and θ_0 are less than the saturated values). The frequency distribution of K_0 was found to be highly skewed over the 150 hectares studied. Estimates of the mean and standard deviation, assuming a log normal distribution, were 26.2 and 30.8 cm/day, respectively, for the 180 cm depth. A combination fractile diagram and cumulative probability distribution for α is given as Figure 3 after Warrick, Mullen and Nielsen (1977 a). Values are plotted using both α and $\ln \alpha$. If the plot with α was a straight line, we would have a normal distribution; if the plot of $\ln \alpha$ gave a straight line, we would have a log normal distribution. The general conclusion is that the population was better approximated by a log normal distribution. The estimate of the overall mean and standard deviation was 75.2 and 67.8.

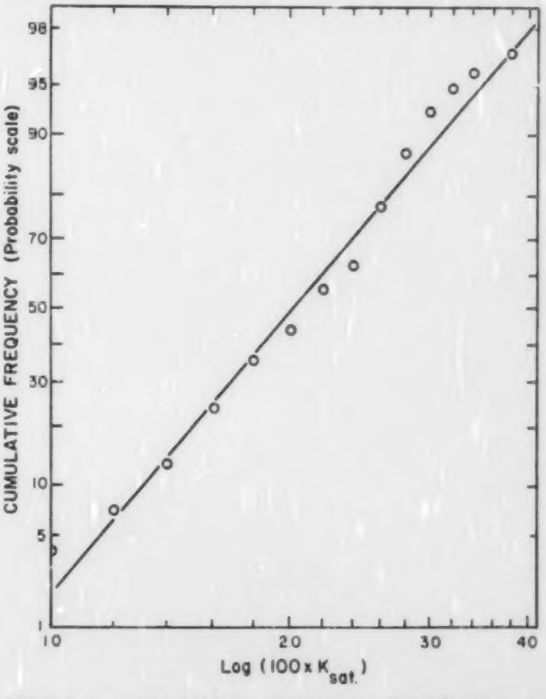

Figure 2. Cumulative frequency distribution of logarithm of the saturated conductivity over 87 hectares of Pima clay loam (After Coelho, 1974).

In an effort to describe soil heterogeniety with one stochastic parameter, Peck, Luxmoore and Stolzy (1977) and Warrick, Mullen and Nielsen (1977 b) utilized a similar media concept after Miller and Miller (1955, 1956). Similar media have pores and grains which differ in size but have the same relative geometry including equal porosity. Consequences are that at a given water content the pressure head h_r (cm) is related to an average pressure head h_m (cm) by

$$\lambda_r h_r = \bar{\lambda}\ h_m \qquad [2]$$

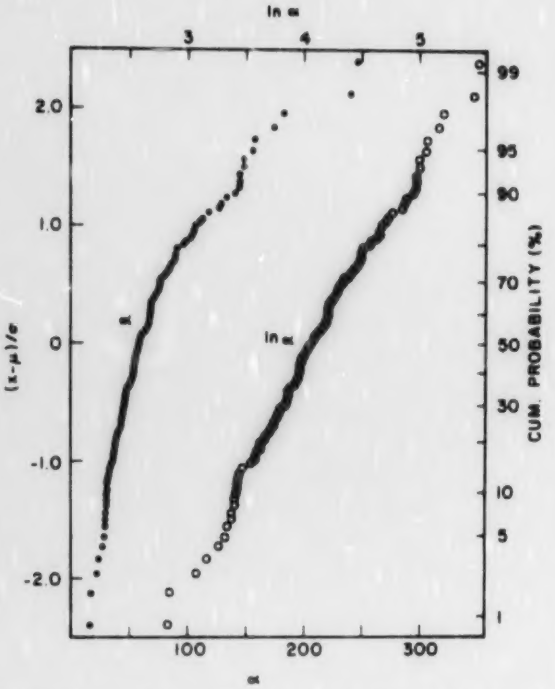

Figure 3. Fractile diagram and a cumulative probability distribution for α and $\ln \alpha$ for 150 hectares of Panoche soil (After Warrick et al., 1977a).

where λ_r is a scaling factor and $\bar{\lambda}$ is the average scaling factor. Similarly, the unsaturated hydraulic conductivity at a given water content would be given by

$$K_r/\lambda_r^2 = K_m/\bar{\lambda}^2 \qquad [3]$$

where K_m is an "average" conductivity and λ_r and $\bar{\lambda}$ are the same as in [2]. The $\lambda_r/\bar{\lambda}$ thus is the only variable describing the soil heterogeneity. For expediency, Peck et al. took the distribution of $\lambda_r/\bar{\lambda}$ to be normal and pursued a water balance analysis on that basis. Warrick et al. determined the "best fitting" set of values of $\lambda_r/\bar{\lambda}$ for three sets of field data collected in three different states in the U.S. These were data of Nielsen et al. (1973), Coelho (1974) and Keisling (1974). Figure 4 shows the results for the 180 depth of Nielsen et al. for the water pressure ($h_{r,i}$) vs. soil water content expressed as degree of saturation $S_{r,i}$. Figure 4A is for the raw data and 4B is for the "best-fitted" data using [2]. The sum of squares is reduced between the data points and the scaled values by approximately 90%. A coalescence of widely scattered points into a relatively narrow band was found for all cases studied including that for unsaturated hydraulic conductivity vs. degree of saturation. However, the set of $\lambda_r/\bar{\lambda}$ found from h vs. S data was not the same as that found for reducing the K values, although there was a strong correlation. The distribution for $\lambda_r/\bar{\lambda}$ values in every case was found to be skewed and approximately log normal. Estimates of the mean and standard deviation for the $\ln(\lambda_r/\bar{\lambda})$ of Figure 4 were found to be -0.14 and 0.51.

RAMIFICATIONS OF VARIABILITY ON WATER FLUX

We now examine distribution of water flux in the soil profile resulting as a consequence of spatial variability. For our illustrations, we consider two different examples. In each case, we assume the unsaturated hydraulic conductivity is given by [1], i. e. $K = K_0 \exp[\alpha(\theta - \theta_0)]$. The α and K_0 take on different values depend-

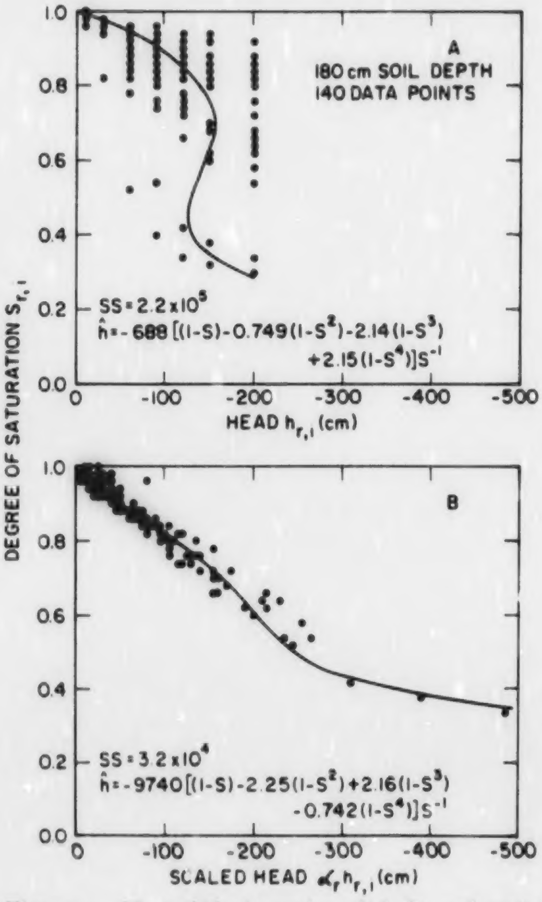

Figure 4. Unscaled (A) and scaled (B) soil water characteristic using the similar media concept (After Warrick et al., 1977b)

ing upon the site location within the area considered. The distribution of α and K_0 are each assumed to be log normal with values of 3.91, 0.636, 2.48, 1.40 for mean of $\ln \alpha$, standard deviation of $\ln \alpha$, mean $\ln K_0$ and standard deviation of $\ln K_0$, respectively. These are all estimates based on the 180 cm depth for the Panoche site (Nielsen et al. 1973; Warrick et al., 1977a).

Example 1. Water Initially Ponded

This is the example discussed in detail in Warrick et al. (1977a). We assume surface ponding sufficiently long that a steady flow rate $J_L = K_0$ exists throughout the profile at each location. From site to site, J_L will take on different values and in fact will be log normally distributed. Figure 5 is a histogram showing the arbitrary classes for t = O and t = 10 days. For t = O (Part A), the distribution of J_L is just that of the K_0 itself. Even though the mean value is 26 cm/day, 45% of the time the flux is less than 10 cm/day and the remaining 35% greater. Thus, the high velocity regions are contributing a disproportionate share of the total areal flux.

At time zero, the ponded water is gone and the profile drains with negligible surface evaporation. A simplified drainage equation based on a unit hydraulic gradient has been shown by Nielsen et al. (1973) to be a reasonable approximation for these conditions:

$$J_L = K_0/(1+\alpha K_0 t/L) \qquad [4]$$

where α and K_0 are as in [1], t is time and L the depth at which J_L is evaulated.

The flux distribution is simulated using Monte Carlo methods as described, for example, by Hammersley and Handscomb, (1964). A total of n random values of K_0 and then of α are chosen from the appropriate log normal distributions. The distribution of these "n" values of J_L may then be examined over a given time and the mean and variance estimated.

Figure 5 B shows the resulting flux distribution of J_L for such a Monte Carlo sample of n = 200 and for t =10 days. The mean value is 0.39 cm/day. The first and second classes make up about 20 and 40% respectively, of the total population. Thus, the distribution is skewed for this time just as for t = 0. Roughly 60 percent of the values are below the mean and 40 percent greater.

The mean value of J_L as determined from Monte Carlo simulations with n = 2000 for 1, 5, 10 and 20 days are shown as the "solid" curve of Figure 6. The vertical bars show the range of the middle 50% of the values. Therefore, 25% of the flux values at each time are greater than the value for the top of each bar and 25% are below the base of the bar. The dashed line is the "deterministic" values obtained by substituting the mean value of α and K_0 into [4]. The mean value and the deterministic curve start together at t = 0 but diverge with time. The true mean is consistently above the other curve. These differences are not a result of an inaccurate determination of the mean, but correlates sample size to expected accuracy for J_L determined at t =0, 1 and 10 days. Assumptions include a sufficient number of samples such that the

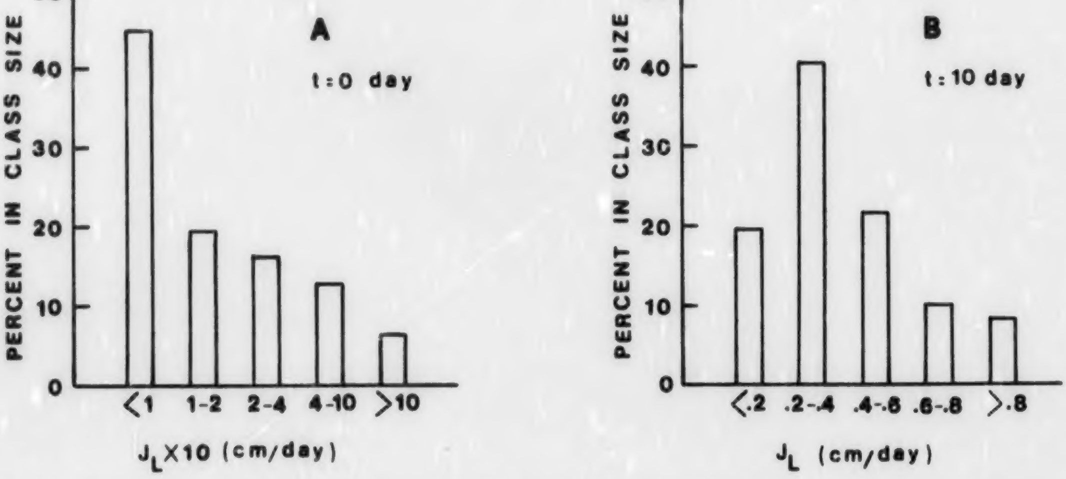

Figure 5. Frequency distribution patterns for 180 cm depth of Panoche soil at t = 0 and t = 10 days.

"central limit" theorem is applicable, that is, n is sufficiently large that estimates of the mean of J_L are normally distributed for variance Var $(J_L)/n$ even though J_L itself is not normally distributed. Examining the results for $t = 0$, we find a sample of 1000 would give an estimate within 5 cm/day (about 16% of the true mean), 95% of the time. Similarly, samples of 100 and 50 would be within 16 and 22 cm/day. At $t = 1$ and $t = 10$ days, a sample of 1000, 100, and 50 would result in estimates within about 4, 14 and 20% of the true mean.

Example 2. Constant Areal Flux Initially

We now consider flux over the entire area at $t = 0$, such as might exist under sprinkler irrigation. At time zero, the irrigation is stopped and drainage allowed. The flux as a function of time is

$$J_L = I_0/(1 + \alpha I_0 t/L) \qquad [5]$$

where I_0 was the initial sprinkling rate. Eq. [5] is simpler than [4] in that α is the only variable parameter.

The mean value of J_L was determined by a Monte Carlo simulation, normalized by I_0 and plotted as a function of time in Figure 8 with $I_0 = 2.6$ cm/day. At $t = 0$, all of the J_L values are simply the constant I_0. As time progresses, we see effects of variability. The mean values are again consistently above the deterministic value found by substituting the mean α value into [5]. Also shown as the shaded region is a band of values corresponding to the middle 50% of the flux values can be found analytically in this case since the high 25% of J_L values correspond to the low 25% of α values and vice versa.

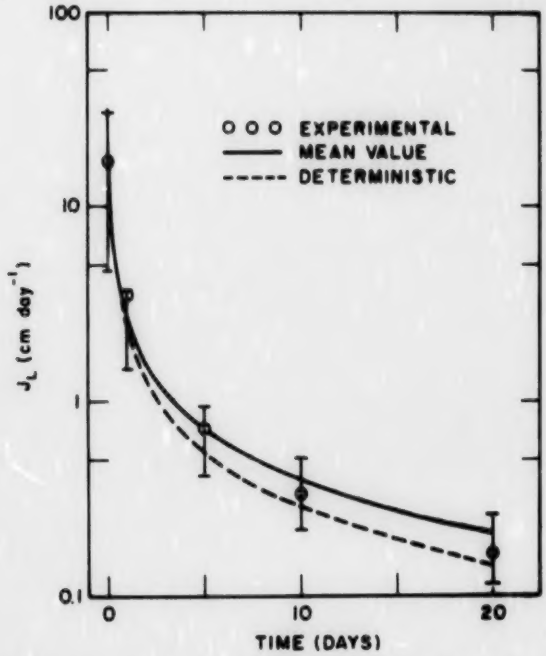

Figure 6. Flux values for Example 1 as a function of time. Bars are ranges of the middle 50% of values (After Warrick et al., 1977a).

DISCUSSION AND CONCLUSIONS

Spatial variation of soil water parameters exist, and as a result, variation of fluxes occur within the profile irregardless of how water is added. Results presented here are for variation

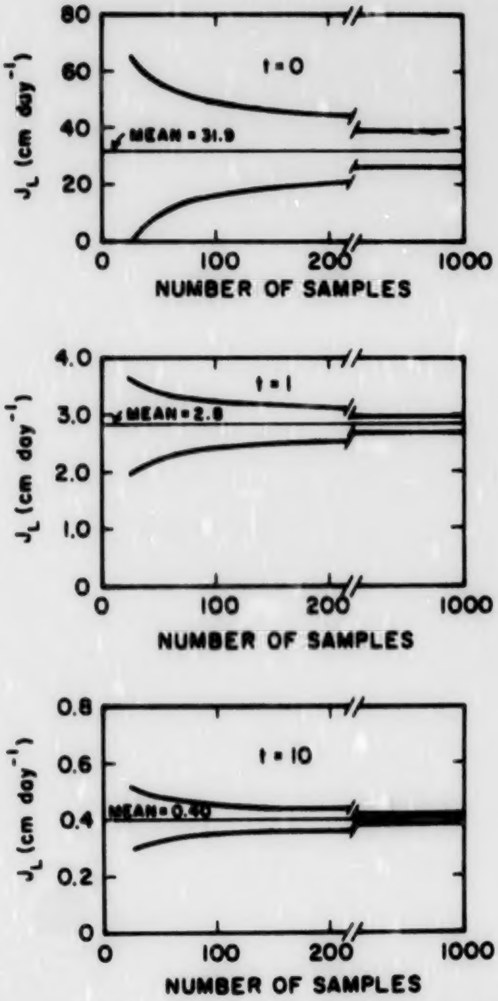

Figure 7. Mean values of J_L, expected 95% of the time for $t = 0$, 1 and 10 (After Warrick et al., 1977a).

in lateral directions, but, of course, vertical stratification also occurs. Our initial moisture condition and subsequent drainage was simple compared to a realistic seasonal field moisture regime. In addition, the approximate drainage equations [4] and [5] facilitated numerical ease for the Monte Carlo simulations. Nevertheless, the results should be indicative of variations under more complex conditions.

In some applications, the estimate of the mean values might well be the singular important factor. In this case, Figure 6 serves as a guideline, although the large number of samples required seems overwhelming. Effective sample stratification criteria should help. In other problems, the flux distribution pattern itself might be as important as the mean value itself, for example, if ponded irrigation techniques were used, the high intake area could dominate the return flow. Low intake areas might be more subject to salinization.

As far as numerical techniques are concerned, the Monte Carlo technique is powerful and has a long history of successful applications elsewhere. Variance reduction techniques are available for Monte Carlo studies and might be used advantageously when solving the non-linear water flow equation when computer times would be significant for repeated calculations.

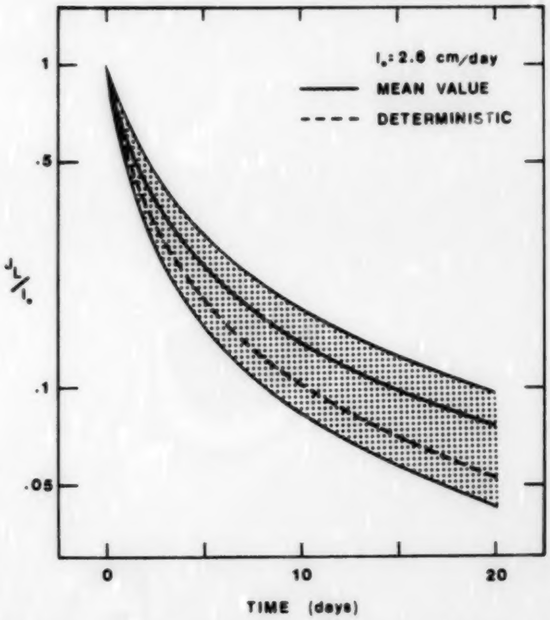

Figure 8. Flux values as a function of time for Example 2. Shaded area is for the middle 50% of values.

ACKNOWLEDGMENT

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Water Distribution Patterns for Sprinkler and Surface Irrigation Systems

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ABSTRACT

A linear fit model for sprinkler and power curve fit model for suface irrigation systems, are suggested to represent actual patterns of distributions in irrigated fields. Both models allow for efficient calculation of surplus and deficient volumes, as well as the various relevant efficiencies.

Both environmental and economical aspects require desired efficiency combinations to be followed and this may be done when the irrigation systems are represented by the suggested models. Also, the various functions related to irrigation performance, may be integrated to reach optimal results.

INTRODUCTION

Most areas in the world are facing food shortages as well as problems with water quality and supply. Overall irrigation efficiencies are known to be low, and better design and evaluation techniques are warranted. Improvement of irrigation efficiency will not only increase the total available water supply, but also have an environmental impact, as well as an increase in yields per unit of land or water.

Irrigation efficiency can be increased by better water management in accordance with proper adjustment of an irrigation system to the given resources and its various parameters. It may be argued that most of the major specific parameters involved in the behavior of different irrigation systems have been studied, thus allowing for the design of better fit irrigation systems. However, due to the newly added environmental features involved in water use, added taxation is due in respect to more efficient uses of water. The use of available information enables an insight into the system's possible performance. However, existing design variables, as well as a lack of sensitivity for specific parameters' effects, do not allow its use toward achieving these goals. Integration of established and available information is required in order to reach an overall strategy allowing system performance evaluation, and adjustment of its parameters to reach higher efficiencies. cies.

From the standpoints of environmental concerns (return flow quality), economics of crop irrigation (lower yields due to excessive soil moisture stresses; fertilizer losses due to deep percolation) and water availability (water losses in the various forms), two main irrigation features may be identified: the application efficiency (E_a) and the spatial water distribution efficiency (E_D).

The field application efficiency is the ratio of the desired application amount to the amount necessary to get this desired application at the minimum point, or the ratio of the amount of water required and the total amount of water actually applied by the system. Field application efficiencies are usually lower when using surface irrigation systems (borders and furrows) and higher with pressure irrigation systems (sprinkler and trickle). The main factors involved in the lower application efficiencies are the runoff and percolating water below the root zone for the surface irrigation system, and the water lost to evaporation, in addition to deep percolation, for the sprinkler and trickle irrigation systems.

The extent of runoff water is primarily a factor of the basic design parameters. It may be

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reused, thus increasing the cost of water, or it may deep-percolate, while degrading the quality of underground water flows.

Under surface (border and furrow) and sprinkler irrigation conditions, the field application efficiencies may be expressed as:

$$E_a = \frac{D \times A}{V} \qquad (1)$$

where D — depth of water made available to plants during irrigation (mm)

A — total area under irrigation (m^2)

V — total amount of water applied.

In tricle irrigation conditions, the field application efficiencies can be expressed as:

$$E_a = \frac{N \times q_{min} \times T}{V} \qquad (2)$$

where N — total number of ticklers

q_{min} — minimum emitter flow rate

T — irrigation time

(q_{min}) and (T) are designed to meet the established water requirements.

The field spatial water distribution efficiency is an evaluation of the uniformity of water distribution in the field, and the factors involved may be classified into those related to the operational practices and those originating in the design. Factors related to the irrigation management and operation tend to average through the irrigation season and a series of irrigation applications. The effects may be difficult to detect in the field and are well recognized only in the later stages, during yield performance. Factors related to design may be considered permanent in their impression on the field, and the extent of damage is obvious and easily estimated.

The field spatial water distribution efficiency (E_D) can generally be expressed as:

$$E_D = \left[1 - \frac{\overline{\Delta D}}{\overline{D}}\right] \qquad (3)$$

where $\overline{D}$ — average depth of water applied by the system

$\overline{\Delta D}$ — average deviation from average depth of water applied by emitters (sprinklers, ticklers) or water stored by furrows or borders.

The field spatial water distribution or pattern reflects on two major parameters: deficient water application, and deep percolating water. Deficient water application is normally associated with excessive moisture stress and salt accumulation. Both may result in yield decrease, but the relationship between soil moisture stress and maximum yield is such that net profit may be maximized at a moisture stress level yielding below the maximum (Stewart and Hagan, 1973). Also, salt accumulation may be periodically leached, thus avoiding yield damages. Deep percolating water contributes to the cost of irrigation water per unit of land as that water is pumped, diverted, and conveyed, to be lost to deep percolation, while leaching and causing the loss of valuable fertilizer. Deep percolation may also contribute to drainage problems associated with rising water tables and water-logging of the root zone stratum. Of basic concern is the degradation of irrigation return flows due to the salt leaching of the deep percolating water.

Both application and field distribution efficiencies determine the irrigation quality and are greatly influenced by the pattern of water distribution in the field. It is feasible to identify irrigation systems by the patterns of water distribution and, accordingly, the relationships of the system's performance regarding moisture deficiency, deep percolation and runoff. The purpose of this work was to develop models that may supply patterns of distribution and efficiency parameters for sprinkler and surface irrigation systems.

SPRINKLER IRRIGATION PATTERNS OF WATER DISTRIBUTION

A single nonoverlapping sprinkler has a nonuniform pattern of water distribution, and overlapping of individual patterns is required. Overlapping and uniformity of patterns are achieved by adapted sprinkler and lateral spacings, as well as adjustments to wind velocities and directions, nozzle characteristics, and pressure-discharge relationships.

Sprinkler irrigation distribution patterns have been characterized by various statistical uniformity coefficients based on the characteristics of the distribution. Christiansen (1942) was first to introduce a uniformity coefficient (UCC) to a sprinkler system.

$$UCC = 1 - \frac{\Sigma |y_i - \overline{y}|}{N \times \overline{y}} \qquad (4)$$

$$\text{or } UCC = 1 - \frac{\Delta\bar{y}}{\bar{y}}$$

where $\Delta\bar{y}$ or $\frac{\Sigma|y_i - \bar{y}|}{N}$ — the mean deviation about the mean, $\bar{y}$.

Christiansen's coefficient (UCC) is the most popular one used by decision makers who also regard UCC > 0.70 as satisfactory.

Wilcox and Swailes (1947) suggested another coefficient of uniformity, where the standard deviation (s) replaces ($\Delta\bar{y}$):

$$UCW = 1 - \frac{s}{\bar{y}} \qquad (5)$$

Hart (1961) and Hart and Reynolds (1965) developed a uniformity coefficient (UCH) on the basis of the assumption that precipitation from commonly used sprinklers, under regular spacing conditions, is normally distributed, and that a normal (Gaussian) distribution expression would well approximate the sprinkler precipitation pattern.

The function for a normal distribution can be written as:

$$Y = \frac{N \bullet q}{s\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Y - \bar{y}}{s}\right)^2\right] \qquad (6)$$

where y — the frequency of the occurence of value Y

$\bar{y}$ — mean of Y values

s — standard deviation

N — total number of samples

q — length of class interval.

This function (Eq. 6), for a normal distribution and its shape, can be defined once s and $\bar{y}$ are known, and various parameters related to applied water ratios and fractions of wetted areas may be determined.

It is pointed out, as follows, that, when the samples have a normal distribution, the mean of the absolute values of deviation equals 0.798 s, and uniformity coefficient (UCH) is suggested:

$$UCH = 1 - \frac{0.798\, s}{\bar{y}} \qquad (7)$$

Hart (1961) and Seniwongse et al. (1972) found that distributions of many practiced sprinkler systems are normal, and they established the relationship between UCC and UCH as:

$$UCC = 0.030 + 0.958\, UCH \qquad (r^2 = 0.888) \qquad (8)$$

It is also indicated that the high correlation allows for reliable prediction equations. Assuming normal distributions, the $s/\bar{y}$ ratio is reported for each analysis, determining the shape of the normal distribution curve. This allows the determination of various irrigation parameters, such as fractions of area adequately irrigated, and a generalized table based upon the normal distribution concept may be constructed.

The model. the purpose of this work is to suggest a model with a standard function whose properties will enable the characterization of precipitation patterns of sprinkler irrigation systems, mainly in reference to efficiency and other irrigation quality parameters.

The model requirements are the establishment of dimensionless cumulative frequency curves (Figs. 1 and 2), representing relationships between precipitation distributions, and the description of these frequency curves by a mathematical model.

The linear regression functional form (Eq. 9) was chosen to express the relationships between the involved variables (Fig. 1):

$$Y = a + bX \qquad (9)$$

where Y — dimensions precipitation depth

X — fraction of area

a,b — linear regression coefficients (constants).

The least squares method (minimization of sum of squares of deviations of estimated values from the observed ones) is used to fit the straight line (linear regression) to the frequency curve of the dimensionless, Y versus X values.

Various other exponential functional forms were also studied, but it was established that the linear regression model fit best to most sprinkler irrigation patterns covering a wide range of $s/\bar{y}$ values.

The dimensionless sprinkler frequency curve usually takes the "S" shape, as the distribution pattern usually tends towards a normal distribution. The $s/\bar{y}$ has a relatively small value when the pattern is highly uniform and most of the distribution is about the mean.

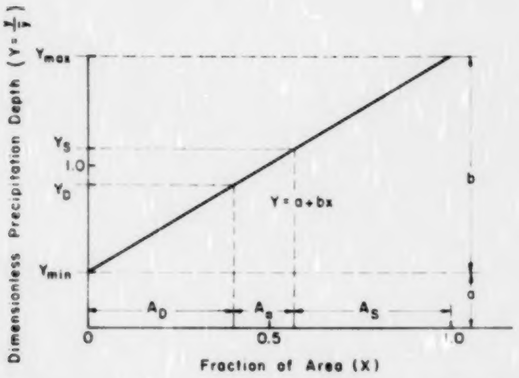

Figure 1. Linear regression fit of a normalized nondimensional distribution curve in sprinkler irrigation.

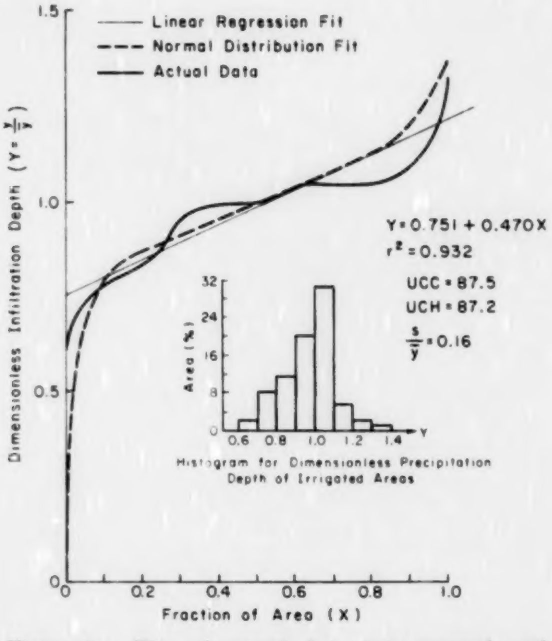

Figure 2a. Fits of actual data into normal and linear regression distribution in sprinkler irrigation.

However, when the pattern tends to be less uniform, $s/\bar{y}$ would increase as the deviation from the mean is larger, and the "S" shape of the distribution curve would stretch out to behave more like a straight line.

It may be hypothesized that the normal fit would be most suitable for distributions where $s/\bar{y}$ tends to be small. However, the linear fit may be just as good, as most of the distribution curve would tend to concentrate around the mean, and errors at both extremes of the frequency curve would be relatively limited. For distributions where the s/y is larger (less fitted to normal), the linear fit would better predict the overall distribution pattern, as errors on both extremes of the frequency curve would be of smaller magnitude.

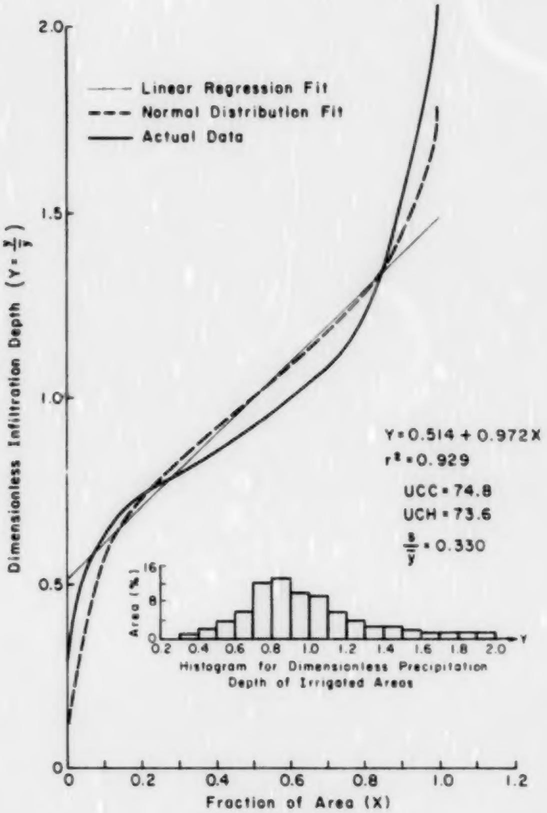

Figure 2b. Fits of actual data into normal and linear regression distributions in sprinkler irrigation.

The suggested model, based on the linear regression fit (Eq. 9), and using the least squares technique, imbeds properties in it that serve to reach valuable information regarding the performance of each specific sprinkler system (Figs. 1 and 3).

1. For $\bar{Y} = 1.0$ (average precipitation depth entering the soil profile = depth designed to replenish soil moisture deficiency), X = 0.5 (half of the area irrigated).
2. The regression coefficient, b (slope of the line), represents $Y_{max} - Y_{min}$ (difference between minimal and maximal wetting zones of the field).
3. The regression coefficient, a, (Eq. 9) is the estimated minimal precipitation

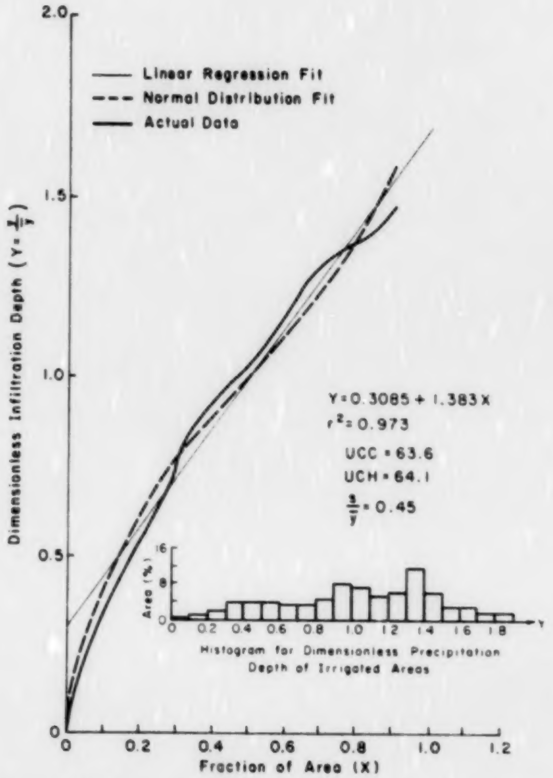

Figure 2c. Fits of actual data into normal and linear regression distributions in sprinkler irrigation.

depth (Y_{min}) and also $Y_{min} = 1\text{-}0.5b$ as $[a + (a+b)] / 2 = 1.0$.

4. The estimated maximal precipitation depth (Y_{max}) equals a + b and also $Y_{max} = 1 + 0.5b$.
5. When $b = 2.0$, Y_{min} will equal 0. Accordingly, when $b > 2.0$, Y_{min} will equal parts of the field will not receive any precipitation ($Y = a + bX$ will show negative values). Also, both average deficit and surplus precipitations can be derived by substituting 0.25 and 0.75 for X.

A distribution coefficient (UCL) is suggested to describe the uniformity of distribution when the precipitation cumulative frequency curve is fitted into a linear regression.

Substituting $\frac{\Sigma | y i - \overline{y} |}{N}$ in Equation 4, from Figure 1:

$$UCL = 1 - \frac{2}{\overline{y}} \left[\tfrac{1}{2} \times 0.5 \left(y_{max} - \overline{y} \right) \right] \qquad (10)$$

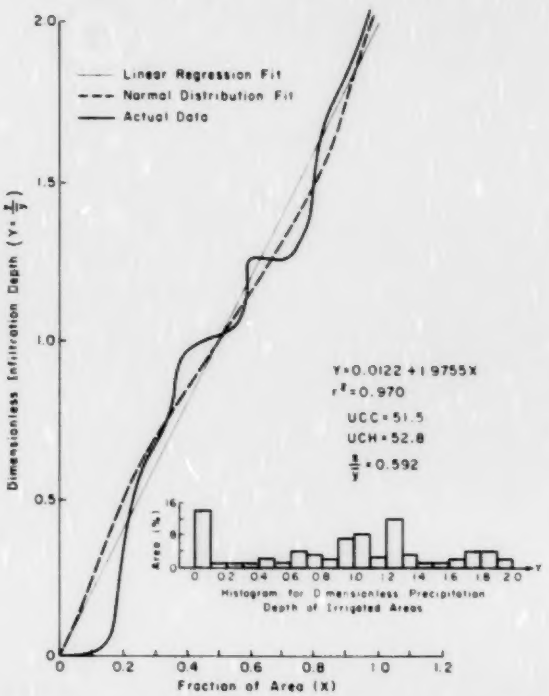

Figure 2d. Fits of actual data into normal and linear regression distributions in sprinkler irrigation.

and $UCL = 1 \; 1 - \frac{0.5}{\overline{y}} (y \, max - \overline{y})$.

Since $\overline{y} = 1.0$ and $y_{max} - \overline{y} = 0.5b$:

$$UCL = 1 - (\tfrac{1}{2} \times 0.5b)$$

or $UCL = 1 - 0.25b$ (11)

and $b = 4.0 - 4.0 \, UCL$ (12)

Relationships between Y max , Y min , b and UCL are given in Figure 3.

Linear regression frequency curves are given in Figure 4 for different uniformity coefficients (UCL), as derived from the linear regressions: 50 percent, 60 percent, 70 percent, 80 percent, 90 percent and 95 percent, and the fraction of irrigated area, X, to given dimensionless precipitation depth, Y. Figure 4 can be used to determine application efficiencies once magnitudes of under-irrigated areas have been established as design criteria.

To study the suggested model and coefficient of uniformity, 19 sets of single sprinkler patterns were chosen, The sprinklers operated under varying pressures (40, 50, 60 psi) and varying wind velocities, and using a computer

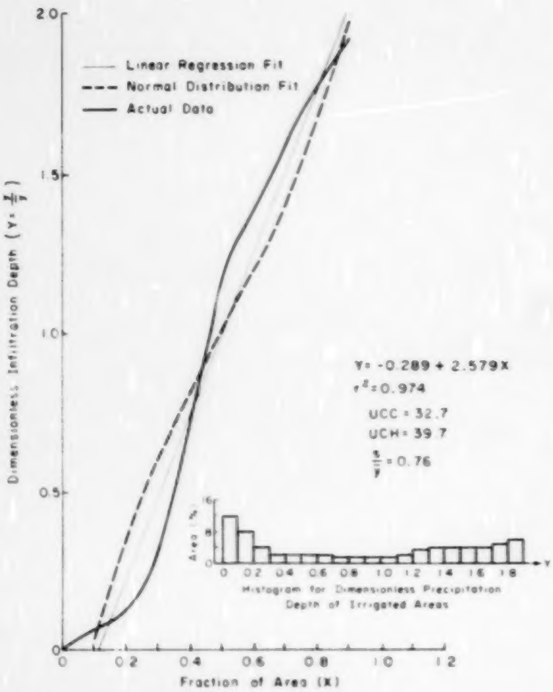

Figure 2e. Fits of actual data into normal and linear regression distributions in sprinkler irrigation.

program, it was overlapped into various spacings (20', 30', . . .70') x (20', 30', . . .70') as well as various geometrical arrangements (rectangular and triangular). The total number of combinations studied was 798.

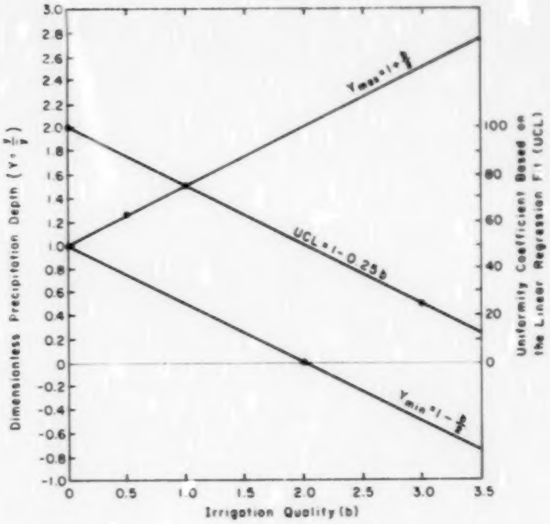

Figure 3. Uniformity coefficient (UCL) as related to irrigation quality in sprinkler irrigation.

The actual data for each combination is transformed into a dimensionless frequency curve and fitted into both linear regression and normal fits. UCC and s/ȳ values are also given. The linear regression fit was found to fit the frequency curve very well. The determination coefficient, r^2, was < 0.800 for only 5.12% of the 798 patterns; 0.800-0.899 for 14.15%; 0.900-0.949 for 28.90% and > 0.950 for 51.83% of the patterns.

Table 1 and Figure 2a-e present a sample of five sprinkler patterns with UCL values ranging from 0.355 to 0.882. Results of the two different fits were compared to the actual data, yielding the overall differences between the actual and the normal (ΣN^2) and linear (ΣL^2) fit values. The normal fits do not exhibit smaller

TABLE 1

Differences between actual, linear (ΔL) and normal (ΔN) distributions for the various fraction of area, X.

Sprinkler Pattern		$\frac{s}{\bar{y}}$	UCC	UCH	UCL	b	r^2	Fraction of Area, X .1	.2	.3	.4	.5	.6	.7	.8	.9	$\Sigma\Delta L^2$	$\Sigma\Delta N^2$
a		0.16	87.5	87.2	88.2	0.470	0.932											
	ΔL*							0.03	0.028	-0.045	-0.034	0.013	-0.045	0.002	0.049	-0.003	0.009	
	ΔN*							-0.001	0.030	-0.089	-0.031	0.009	-0.056	-0.012	0.039	0.010		0.009
b		0.33	74.8	73.6	75.7	0.972	0.929											
	ΔL							-0.047	-0.054	-0.017	0.019	0.055	0.072	0.060	0.041	-0.156	0.046	
	ΔN							-0.055	-0.013	0.031	0.059	0.082	0.086	0.065	0.054	0.094		0.037
c		0.45	63.6	64.1	65.4	1.383	0.973											
	ΔL							0.095	0.037	-0.045	-0.073	-0.057	-0.042	-0.037	0.040	0.080	0.035	
	ΔN							0.075	0.079	0.000	-0.045	-0.053	-0.062	-0.072	0.007	0.108		0.038
d		0.59	51.5	52.8	50.6	1.976	0.970											
	ΔL							0.115	0.023	-0.069	-0.160	-0.011	-0.054	0.143	0.052	-0.039	0.058	
	ΔN							0.145	0.116	0.014	-0.116	-0.012	-0.103	0.058	-0.044	-0.072		0.100
e		0.76	32.7	39.7	35.5	2.579	0.974											
	ΔL							-0.065	0.095	0.164	0.056	-0.175	-0.114	-0.051	0.011	0.113	0.099	
	ΔN							-0.034	0.234	0.283	0.124	-0.174	-0.179	-0.168	-0.125	0.052		0.260

* ΔL = Difference between actual and linear regression fit values for X = 0.1-0.9

ΔN = Difference between actual and normal distribution fit values for X = 0.1-0.9

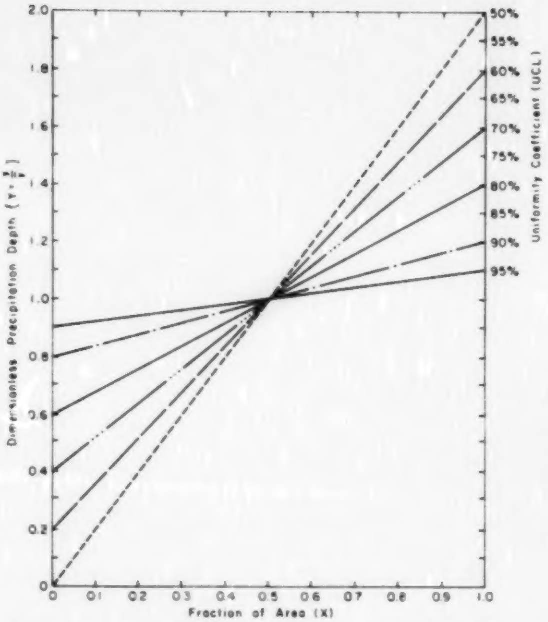

Figure 4. Uniformity coeffiecients assuming linear relationships between precipitation depth and area irrigated in sprinkler irrigation.

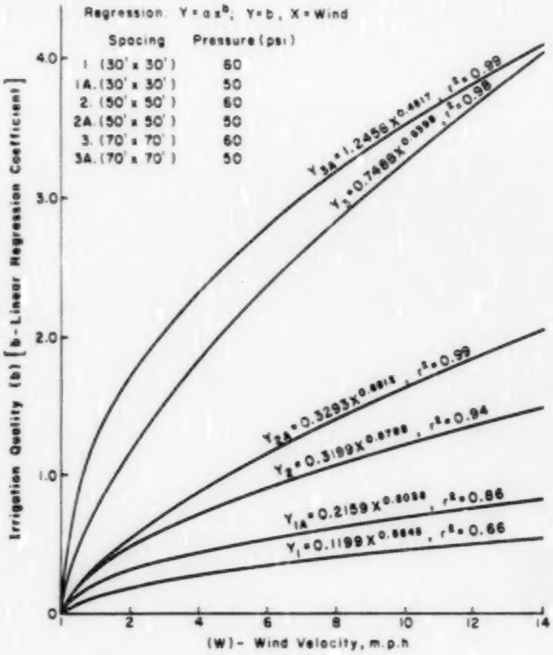

Figure 5. Irrigation quality (b) as a function of wind velocity for varying spacings and pressures in sprinkler irrigation.

deviations from actual data than the linear fit. Where s/y is significantly larger (patterns d and e) the linear fit is much better. However, there is a tendency for smaller deviations at the extremes, when the normal fit is exercised, while the rest and major portions of the field tend to lesser errors, with the linear regression fits.

Various relationships were established from this study:

$$b = 3.956 - 3.940 \text{ UCC} \qquad (r^2 = 0.998) \qquad (13)$$

where b — coefficient of the linear regression for the dimensionless frequency curve.

Equation 13 shows great similarity to the theoretical Equation 12.

$$b = 4.170 - 4.180 \text{ UCH} \qquad (r^2 = 0.999) \qquad (14)$$

The "b" values derived (representing irrigation quality or patterns) are related in Figure 5 to wind velocities for various spacings and pressures to allow their use in decision-making.

The linear regression model allows for the evaluation of the distribution pattern (UCL), as well as reaching valuable irrigation decisions on the basis of results from the given function.

TABLE 2

Estimates of Water and Area Distribution for Five Sprinkler Patterns (Fig. 2a-e).

Efficiency and System Quality	*Sprinkler Pattern*				
	a	*b*	*c*	*d*	*e*
UCL	88.2	75.7	65.4	50.6	35.5
b (Y = a + bX)	0.470	0.972	1.383	1.976	2.579
Y_{min} (estimate)	0.775	0.536	0.378	0.111	0.000
Y_{min} (actual)	0.717	0.551	0.233	0.048	0.026
Y_{max} (estimate)	1.198	1.411	1.622	1.889	2.161
Y_{max} (actual)	1.252	1.715	1.677	1.975	2.153
Deficiently watered area ($Y < 0.0$)	0.316	0.397	0.427	0.449	0.461
Average watered area ($Y = 0.9 - 1.1$)	0.426	0.206	0.146	0.102	0.078
Surplus watered area ($Y > 1.1$)	0.258	0.397	0.427	0.449	0.461
Increase to bring 100% area to Y_D	1.16	1.68	2.38	8.11	—
Increase to bring 90% area to Y_D	1.13	1.47	2.01	4.29	∞
Percent volume in deficient zone	0.261	0.281	0.258	0.205	0.141
Percent volume in average zone	0.440	0.206	0.146	0.102	0.078
Percent volume in surplus zone	0.299	0.513	0.596	0.693	0.781
Percent volume in excess	0.018	0.099	0.152	0.308	0.274

Deficient and surplus volumes, in relation to area fractions, as well as changes required to adjust to requirements, may be reached using some of the following relationships:

Area deficiently irrigated, $A_D = \frac{Y_D - a}{b}$

where Y_D — maximal precipitation in the area irrigated deficiently.

Area irrigated in surplus, $A_S = 1 - \frac{Y_S - a}{b}$

where Y_S — minimal precipitation in the area irrigated in surplus.

Area irrigated, as designed (± deviation),

$$A_A = 1 - (A_D + A_S).$$

Average application in the surplus area,

$$\overline{Y}_S = \frac{Y_S + 1 + \frac{b}{2}}{2}$$

Average application in the deficient area,

$$\overline{Y}_D = \frac{Y_D - 1 + \frac{b}{2}}{2}$$

Volume estimates may be obtained if total area (A_T) and average application rate (D_A) are given. The excess volume applied (V_S) would be:

$$V_S = \frac{Y_{max} - Y_S}{2} \bullet D_A \bullet A_S \bullet A_T$$

Some of these estimates are given in Table 2, for the patterns shown in Figure 2a-e.

SURFACE IRRIGATION PATTERNS OF WATER DISTRIBUTION

The two most common parameters for describing the quality of surface irrigations have been the water application efficiency (E_a), as shown in Equation 1, and the water distribution efficiency (E_D), as shown in Equation 3. Although the above efficiency parameters provide an insight into irrigation system performance, they are lacking in several respects, namely:

1. The amount of deep percolation or deficient volumes of infiltrated water in an irrigated field cannot be deduced.
2. The actual distribution in infiltrated depth of water throughout the field cannot be established.

Thus, a need exists for a technique which will describe distribution patterns and efficiencies. The technique must be able to:

1. Aid in developing optimal design of irrigation systems based on computation of:
    a. Amount and distribution of deep percolation water volumes
    b. Amount and distribution of underirrigated root zone volumes
    c. Volume of runoff losses.
2. Aid in evaluation of already-designed systems and evaluation of operational variable changes on the performance.

A perfect irrigation would be one in which each of the efficiency parameters are a unity. These parameters are: the water requirement efficiency (EDV), the deep percolation efficiency (EDP), the tail water efficiency (ETW), and the overall application efficiency (EB). The efficiencies are given by the following equations.

EB = $E_a/100$
EDV = 1 - VDF/VRZ
where VDF — Total deficient volume of water in root zone after irrigation
VRZ — Total amount of water needed by root zone to reach field capacity.
EDP = 1 - VDP/VLI
where VDP — Total volume of deep percolation
VLI — Total volume of infiltration.
ETW = 1 - QRF/TVL
where QRF — Total runoff volume
TVL — Total volume applied to field.

The optimal combination of efficiencies to provide maximum benefit in any irrigation system is dependent on many factors. EDV is dependent on the loss in productivity due to crop stress and salt accumulation. EDP is a function of water cost, possible increased drainage costs, loss of fertilizers, and reduction in yield due to lost fertilizers. ETW is dependent on cost of water, cost of water application, cost of reuse and availability of water.

The primary factors which affect the distribution of infiltrated depth of water throughout irrigated fields in surface irrigation are many:

1. Soil infiltration characteristics
2. Slope
3. Roughness
4. Geometric configuration of channel or width of border
5. Desired depth of application
6. Length of run
7. Volume inflow
8. Total time of application (total volume applied).

An example of the potential effects on the distribution of infiltrated water with varying operational characteristics in an irrigation system is illustrated in Figure 6, where only one parameter, volume inflow, varies.

The distribution of water in an irrigated field may be computed without resorting to actual field measurements if the following are known:

1. Rate of advance of the irrigation front
2. Infiltration characteristics of soil
3. Rate of recession of water from the soil surface.

Several authors have proposed methods for estimating the rate of advance in furrows and borders. Bassett (1972) has proposed a model which accounts for both mass and energy of the advancing water, and volume balance procedures have been proposed by several authors. Among these are Hall (1956), Wilke and Smerdon (1965) and Bishop and Fok (1965). Although these authors make a seemingly gross assumption that the momentum can be accounted for by assuming a constant average depth of surface storage, their comparisons with field data indicate that these methods yield a good approximation of irrigation advance for most cases.

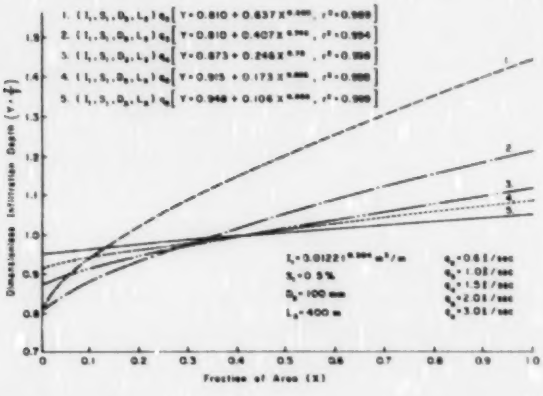

Figure 6. Power curve fit expressions for varying discharges in furrow irrigation ($Y = C + aX_b$).

In this study, the method proposed by Wilke and Smerdon (1965) was used to simulate advance on irrigation furrow because of its ease of application and close approximation to field data. The equation established by Wilke and Smerdon is a solution of the Lewis and Milne volume balance equation as proposed by Philip and Farrell (1964). The general equation proposed by Philip and Farrell is:

$$\frac{cx}{qt} = \sum_{m=0}^{\infty} \frac{\left[\frac{kt^{n}}{c} \bullet \Gamma \bullet (1+n)\right]^{n}}{\Gamma \bullet (2+mn)} \qquad (15)$$

where q — inflow - ft^3/min/furrow in furrow, or inflow ft^3/min/ft in border

c — average area of surface storage, ft^2, for furrow, or average depth of surface storage, in feet, for borders

x — distance of water advance at time t

t — time of advance

k,a — constants of cumulative infiltration equation

n — an integer

Γ — symbol for the gamma function.

Wilke and Smerdon (1965) solved the equation for several values of n and the resulting equation is:

$$\frac{qt}{cx} = 1.0 + A\,\frac{kt^{n}}{c} \qquad (16)$$

where q, t, c, x, k, and n are as defined previously

A — coefficient dependent on the exponent of the infiltration equation. The solution for values of n other than specifically given are obtained through interpolation.

Several empirical equations have been used to describe the infiltration characteristics of soil [Green and Ampt (1911), Gardner and Widstoe (1971), Philip (1957) and Kostiakov (1932)]. The

Kostiakov and modified Kostiakov equations have been the most commonly used equations due to their simplicity and applicability to most field situations. The integrated form of the Kostiakov equation is used in this study.

$$D = 1\ kt^{n} \qquad (17)$$

where k,n — empirically determined constants for a given soil and soil condition

t — total infiltration time

D — cumulative infiltration depth.

Recession in furrows and border irrigation was discussed by Wu (1972) and others. In borders, an estimation of the rate of recession is essential, as the surface storage is usually a substantial portion of the total applied water when the discharge and the head of the border is terminated. In furrows, the volume stored in the furrow is usually a small portion of the infiltrated water. Wilke and Smerdon (1965) assumed a horizontal recession in furrows and stated that the assumption that surface storage is negligible "...would not be satisfactory for small time increments, for soils having very slow infiltration rates or for unusually large furrows or stream sizes." Recession was assumed negligible in this study, as its inclusion was not considered to be essential to the presentation of stated objectives.

The model. As with the sprinkler analysis, the stated purpose of this study was the development of a model for describing distribution patterns and efficiencies. The model requirements are:

1. Establishment of a frequency curve of the dimensionless infiltration depth, Y, versus fractional areas (fractional length of run), X (Fig. 6).
2. Description of the frequency curve by a mathematical model which enables the comparison of systems based on the various efficiencies (EDV, EDP, ETW) and other statistical parameters such as the deviation from desired application depth.

The models considered in this work for describing the frequency distribution are:

1. $Y = aX^{b}$ (18)

where Y — dimensionless infiltration depth = infiltrated depth/desired depth of infiltration

X — fraction of field, wetted

a — coefficient of distribution curve = Y_{max}

b — exponent of distribution.

2. $Y = c + aX^{b}$ (Fig. 7) (19)

where Y, X — as defined above

c — minimum depth ratio (Y_{min})

a — $Y_{max} - Y_{min}$

b — exponent of distribution.

Both models (Eqs. 18 and 19) were fitted to the frequency curves computed when using the Wilke and Smerdon advance equation (Eq. 16) and the Kostiakov infiltration equation (Eq. 17). The curves represented a wide range of combinations for furrow irrigation with varying design and operation variables. (Five comparisons are illustrated in Fig. 8.)

The model $Y = aX^{b}$ was fitted to computed depths with minimum $r^2 = 0.89$, and mostly $r^2 > 0.95$. This equation is inaccurate at very small X, and underestimates Y_{max}. (It is very accurate only when water first reaches the end of the field.) The model of the form $Y = c + aX^{b}$ is more desirable, as the model requirements are better met and it allows for more information.

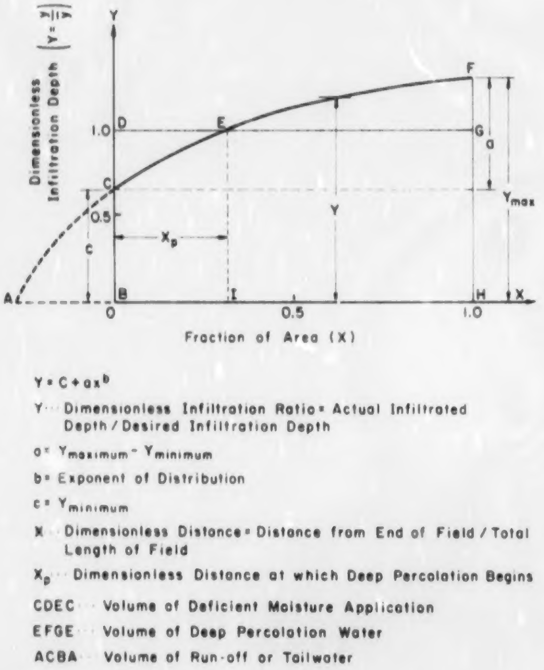

Figure 7. Power curve fit of a normalized distribution curve in surface irrigation.

The minimum application ratio, Y_{min}, in the field is the coefficient, c. The maximum application ratio, Y_{max}, is (c + a).

From the $Y = c + a X^b$ model, the deficient and deep percolated volumes may be obtained, and in many cases the runoff volume and total applied volume may be accurately estimated. *The under-irrigated or deficient volume, DFV,* in Figure 7, is represented by the area CDE. This area is:

$$DFV = CDE = DEIB - CEIB = X_p - CEIB$$

$$\text{where } X_p = \left(\frac{1-c}{a} \right)^{i/b}$$

$$CEIB = \int_0^{X_p} (c + a X^b)\, dX =$$

$$\left[cX + \frac{a}{b+1} X^{b+1} \right]_0^{X_p} = c X_p + \frac{a}{b+1} X_p^{b+1}$$

$$\text{and } DFV = X_p - c X_p - \frac{a}{b+1} X_p^{b+1} \tag{20}$$

The volume of deep percolation, VDP, Figure 7, is represented by the area EFGE and can be computed as:

$$VDP = EFG = EFHI - EGHI \tag{21}$$

$$EFGHI = \int_{X_p}^{1} (c + a X^b)\, dX =$$

$$\left[cX \quad \frac{a}{b+1} X\, b+1 \right]_{X_p}^{1}$$

$$= c + \frac{a}{b+1} - c X_p - \frac{a}{b+1} - a X_p^{b+1}$$

$$EGHI = 1 - X_p$$

$$\text{and } VDP = c + \frac{a}{b+1} - c X_p - \frac{a}{b+1} X_p^{b+1} - 1 + X_p$$

The sum of deviations from the desired infiltrated depth, SDEV, is:

$$SDEV = DFV + VDP$$

The approximate runoff volume, QRF, is represented by the area ACB in Figure 7. This area may be approximated by extending Line CEF to the point where Y = 0. More exactly, this area may be calculated by taking three points along curve CEF for any combination of a, b, c and solving two equations, one of which is solved by trial and error, to obtain a power curve fit $Y_n = A_1 X_n^{B1}$. The following equations apply:

$$\left(Y_1^{1/B_1} - Y_0^{1/B_1}\right) \Big/ \left(Y_5^{1/B_1} - Y_o^{1/B_1}\right) = 2$$

$$A_1 = \left(Y_1^{1/B_1} - Y_0^{1/B}\right)^{B_1}$$

where Y_0 — $Y_{min} = c$
Y_5 — Y at $X = 0.5$
Y_1 — $Y_{max} = c + a$
A_1, B_1 — constants in Equation $Y_n = A X_n^B$.

The distance AB in Figure 7 can then be computed as:

$$X_1 = \left(Y_0 / A_1\right)^{1/B_1}$$

and the runoff (QRF) may then be estimated as:

$$QRF = \int_0^{X_1} A_1 X^{B_1}\, dx = \frac{A_1}{B_1+1} X^{B_1+1}$$

$$\text{or } QRF = \frac{A_1}{B_1+1} X_1^{B_1+1} \tag{22}$$

The total volume applied to the irrigated field, TVL, is represented by the area under the curve ACEF:

$$TVL = \int_0^{X_1+1} A_1 X^{B_1}\, dX =$$

$$\left[\frac{A_1}{B_1+1} X^{B_1+1} \right]_0^{X_1+1}$$

or

$$TVL = \frac{A_1}{B_1+1} (X_1 + 1)^{B_1+1} \tag{23}$$

The volumes computed can be used to calculate the various desired quality parameters, and the following equations apply:

$$EDV = 1 - DFV/VRZ \tag{24}$$

where VRZ — volume desired in root zone =1

EDP = 1 — VDP/VLI

where VLI — total volume infiltrated =Area EFGHI

ETW = 1 — QRF/TVL

$$EB = 1 - \frac{TVL - QRF - VDP - DFV}{TVL}$$

Some results from a series of trials in which only a single design or operation variable at a time was changed are given in Table 3 and Figure 9. The results show that if the distribution of infiltrated depth can be established, EDV and EDP can be closely determined from the equation $Y = c + a X^b$. ETW was found not to correlate as well for some values of c, a, and b. This is probably due mostly to the effect of surface storage and recession which was neglected in this study. However, in the many furrow cases examined, ETW is predicted accurately for cases in which the surface storage is a small fraction of the infiltrated volume. The coefficients c, a, and b in the distribution model are merely an expression of distribution in the irrigated field, and thus the extrapolation of the equation to obtain ETW may not be justified in border irrigation, as recession is an important factor. As an example of when extrapolation would yield totally erroneous results is the case when the rate of recession is approximately equal to the rate of advance. In this case the extrapolation of the distribution in the irrigated field would indicate an infinite volume of runoff.

Since the discharge into a furrow or border is usually known or can be easily measured, ETW can be calculated if the distribution equation is known by the following simple relationship.

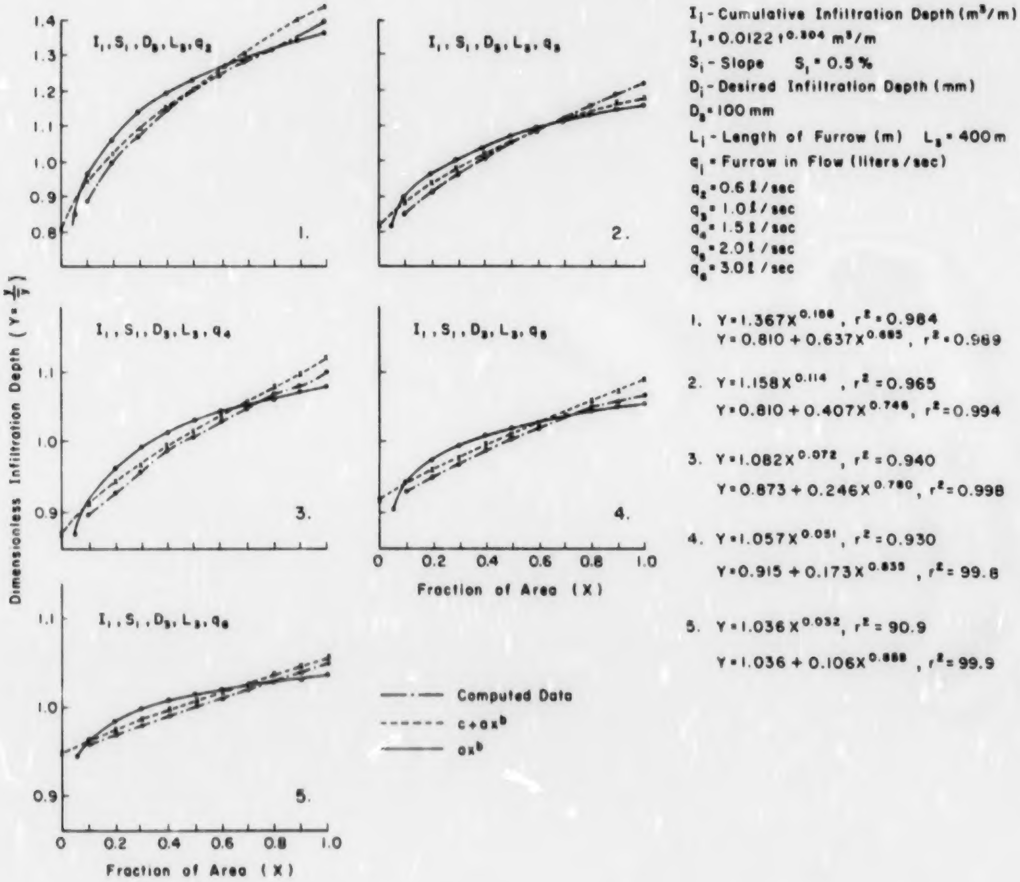

Figure 8. Comparison between fits of computed data into two power curve fits in furrow irrigation.

$$ETW = \frac{1 - (c + \frac{a}{b+1}) \times VDA}{QT} \qquad (25)$$

where VDA — total volume desired in root zone
QT — total volume applied to field.

The calculation of efficiencies through use of the equations may be eliminated, as the efficiencies obtained from any given distribution may be estimated for any combination of a, b and c using graphical presentations (Fig. 9a-e).

Valuable insight into the performance of an irrigation system can be obtained by studying the change in efficiencies with changing design or operation variables (Tabel 3). From this table we see that EDV decreases rapidly from the first time setting to the second for discharges q_2 and q_3. However, to completely fill the root zone requires a substantial increase in the total volume (time) of application. Thus, if a small percentage of deficiency can be tolerated, a substantial decrease in water use is realized.

Relationships of varying irrigation design variables and distribution coefficients (a, b, c) may be plotted (Fig. 10a, b) to enable the designer to compare systems and select the optimal design or operation based on his limitations on EDV, EDP and ETW. In the practical design ranges, the curves for any one system may be established by a few points. The system performance for many different operating conditions may then be deduced. Table 4, in conjunction with Figure 11, illustrates one such analysis. In this analysis weighting factors were assigned to each of EDV, EDP and ETW. The overall performance of an irrigation system (OP) over a range of variable changes can thus be examined. The equation which was chosen as an indicator of system performance in each case is given by:

$$OP = \frac{C_1 ETW + C_2 EDV + C_3 EDP}{C_1 + C_2 + C_3} \qquad (26)$$

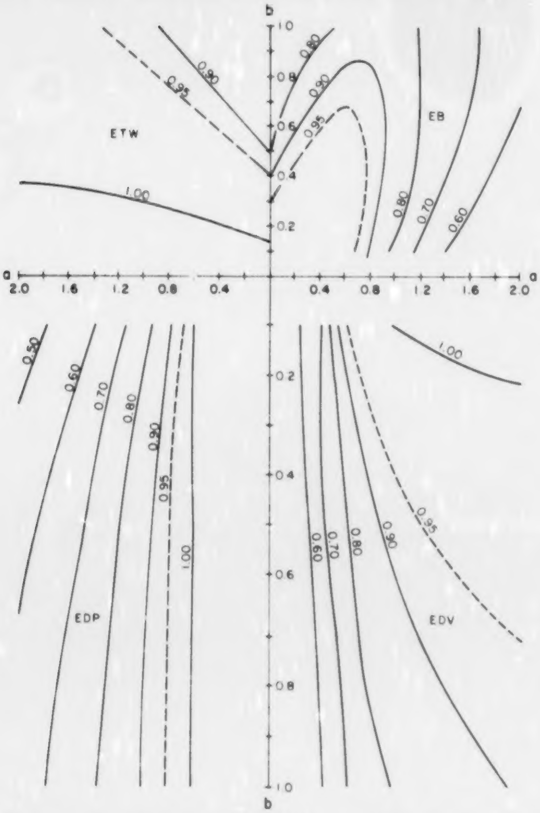

Figure 9a. Surface irrigation quality parameters and distribution coefficients (a, b, c) for minimal application ratio, c = 0.4.

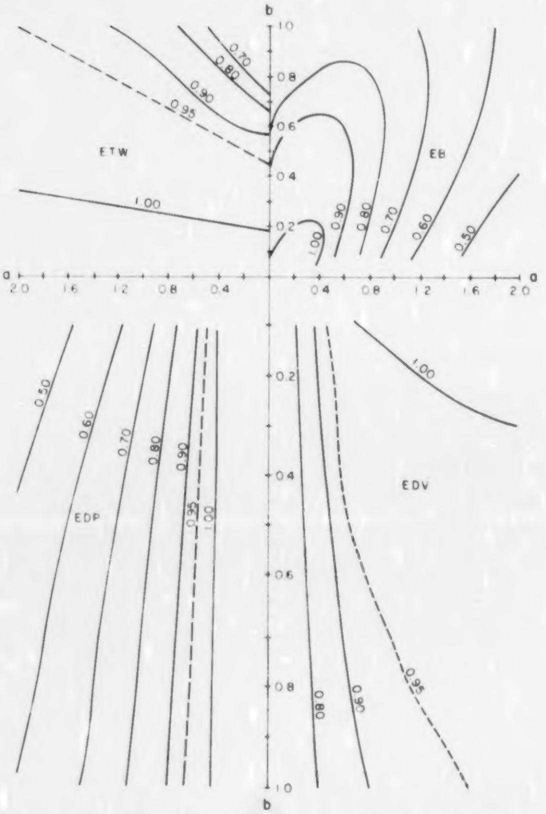

Figure 9b. Surface irrigation quality parameters and distribution coefficients (a, b, c) for minimal application ratio, c = 0.5.

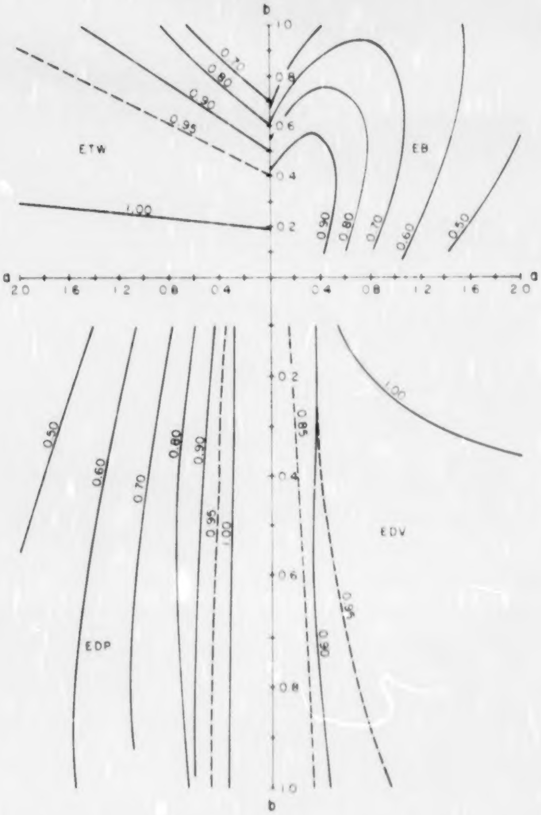

Figure 9c. Surface irrigation quality parameters and distribution coefficients (a, b, c) for minimal application ratio, c = 0.7.

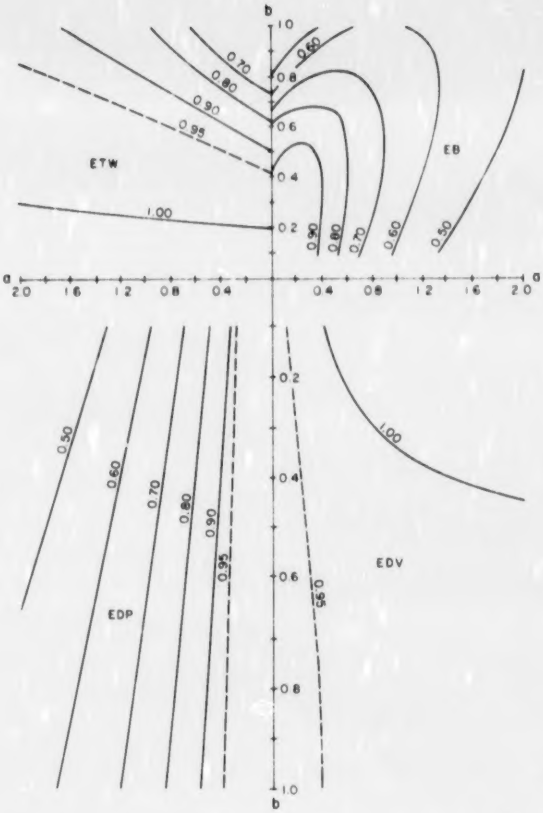

Figure 9d. Surface irrigation quality parameters and distribution coefficients (a, b, c) for minimal application ratio, c = 0.8.

TABLE 3

Comparison between computed and estimated efficiency values.

Total Volume Applied, QTOT	Distribution Coefficient			Water Requirement Efficiency, EDV			Deep Percolation Efficiency, EDP			Tail Water Efficiency, ETW			Design Parameters
	c	a	b	From $Y=c+aX^b$	Computed	Difference %	From $Y=c+aX^b$	Computed	Difference %	From $Y=c+aX^b$	Computed	Difference %	
32.8	0.000	1.34	0.283	0.932	0.938	0.6	0.882	0.883	0.1	1.000	0.960	4.2	I_1 S_1 D_3 L_3 q_2
39.8	0.810	0.637	0.685	0.987	0.987	0.0	0.831	0.832	0.1	0.900	0.894	0.7	" "
46.8	1.000	0.503	0.756	1.000	1.000	0.0	0.785	0.778	0.9	0.830	0.774	7.2	" "
27.8	0.000	1.092	0.287	0.836	0.844	0.9	0.985	0.991	0.6	1.000	0.918	8.9	I_1 S_1 D_3 L_3 q_3
39.5	0.810	0.407	0.746	0.971	0.972	0.1	0.931	0.933	0.2	0.800	0.791	1.1	" "
51.2	1.000	0.308	0.838	1.000	1.000	0.0	0.865	0.857	0.9	0.630	0.683	7.8	" "
35.1	0.680	0.347	0.694	0.883	0.885	0.2	1.000	1.000	0.0	0.830	0.756	9.8	I_1 S_1 D_3 L_3 q_4
47.7	0.873	0.246	0.780	0.976	0.977	0.1	0.965	0.966	0.1	0.690	0.635	8.7	" "
43.6	1.000	0.202	0.856	1.000	1.000	0.0	0.911	0.903	0.9	0.530	0.551	3.8	" "
46.8	0.805	0.212	0.794	0.922	0.923	0.1	1.000	1.000	0.0	0.690	0.592	16.6	I_1 S_1 D_3 L_3 q_4
58.8	0.915	0.173	0.835	0.984	0.984	0.0	0.974	0.976	0.2	0.580	0.515	12.6	" "
70.6	1.000	0.149	0.875	1.000	1.000	0.0	0.936	0.927	1.0	0.460	0.458	0.4	" "

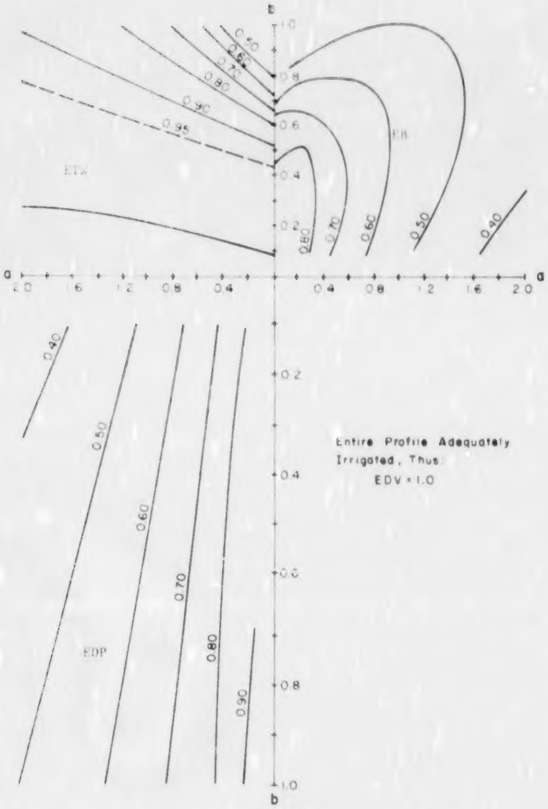

Figure 9e. Surface irrigation quality parameters and distribution coefficients (a, b, c) for minimal application ratio, c = 1.0.

The weighting factors C_1, C_2, and C_3, as shown in Figure 11, were asssigned arbitrarily for purposes of illustration. In practice,these weighting factors would include the many and varied costs and/or benefits associated with the performance of a system at any given set of conditions.

TABLE 4

Overall furrow irrigation performance with changing design and/or operation variables*.

Total Volume Applied QTOT, m³	$I_1\ S_1\ D_3\ L_3\ q_2$							
	$c^{\dagger}$	$a^{\dagger}$	$b^{\dagger}$	ETW	EDV	EDP	$OP_1^{\#}$	$OP_1^{'\S}$
35.0	0.52	0.90	0.50	0.99	0.94	0.915	0.940	0.947
38.0	0.76	0.70	0.66	0.92	0.975	0.835	0.939	0.952
41.0	0.87	0.55	0.77	0.83	0.99	0.825	0.921	0.946
44.0	0.97	0.53	0.75	0.79	0.997	0.820	0.913	0.943
47.0	1.00	0.49	0.75	0.77	1.00	0.815	0.908	0.941

Total Volume Applied QTOT, m³	$I_1\ S_1\ D_3\ L_3\ q_3$							
	$c^{\dagger}$	$a^{\dagger}$	$b^{\dagger}$	ETW	EDV	EDP	$OP_1^{\#}$	$OP_1^{'\S}$
35.0	0.69	0.59	0.60	0.940	0.955	0.90	0.943	0.947
38.0	0.80	0.47	0.73	0.830	0.970	0.91	0.921	0.939
41.0	0.86	0.38	0.80	0.720	0.980	0.89	0.893	0.925
44.0	0.93	0.35	0.82	0.690	0.990	0.87	0.887	0.925
47.0	0.96	0.33	0.83	0.650	0.995	0.865	0.878	0.920
50.0	1.00	0.32	0.84	0.620	1.000	0.86	0.871	0.918

Total Volume Applied QTOT, m³	$I_1\ S_1\ D_3\ L_3\ q_4$							
	$c^{\dagger}$	$a^{\dagger}$	$b^{\dagger}$	ETW	EDV	EDP	$OP_1^{\#}$	$OP_1^{'\S}$
35.0	0.69	0.33	0.68	0.850	0.88	0.99	0.887	0.885
38.0	0.73	0.32	0.73	0.81	0.91	0.98	0.891	0.898
41.0	0.75	0.28	0.73	0.78	0.925	0.97	0.890	0.903
44.0	0.82	0.26	0.74	0.74	0.935	0.96	0.883	0.902
47.0	0.84	0.23	0.75	0.70	0.940	0.96	0.874	0.898
50.0	0.88	0.23	0.80	0.66	0.945	0.96	0.865	0.895

* $$OP_i = \frac{C_1ETW_i + C_2EDP_i + C_3EDV_i}{C_1 + C_2 + C_3}$$

where OP_i----overall performance indicator

ETW----tail water efficiency

EDV----water requirement efficiency

EDP----deep percolation efficiency

C_1, C_2, C_3----assumed weighting factors

† c, a, b = coefficients of distribution

# $C_1 = 1$; $C_2 = 2$; $C_3 = 4$

§ $C_1 = 1$; $C_2 = 2$; $C_3 = 8$

CONCLUSIONS

The models, based on the linear fit for sprinklers and power curve fit for surface irrigation systems, were found to be good representations of actual patterns of distribution in an irrigated field. The models also allow for efficient calculation of surplus and deficient volumes, as well as the various relevant efficiencies. The use of the distribution patterns, as studied by these models, is important when changes in operational or design variables are due. The concept of managing or designing an irrigation system to obtain the desired efficiency combinations rather than designing to always fill the root zone is forthcoming if short water supplies are of any concern.

Based on this work, the following procedure may be followed to describe optimal distribution patterns and efficiencies for surface irrigation systems.

1. Establishment of soil infiltration rate, rate of advance and recession with different inflow rates.
2. Derivation of power curve fit models, using the above infiltration, advance and recession expression. These models

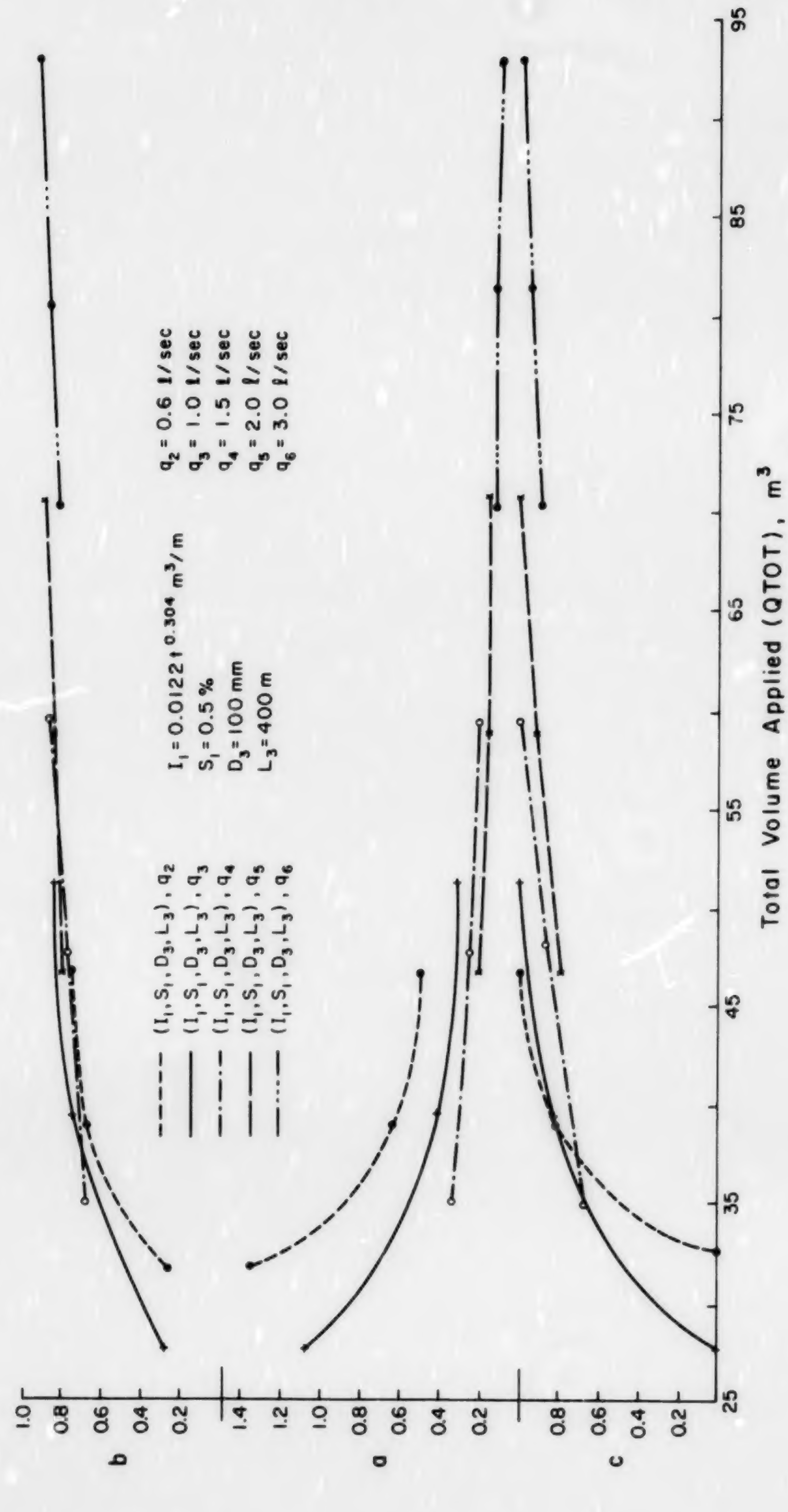

Figure 10a. Variation in distribution coefficients (a, b, c) for varying discharges and total volume (time) applied (QTOT) in surface irrigation.

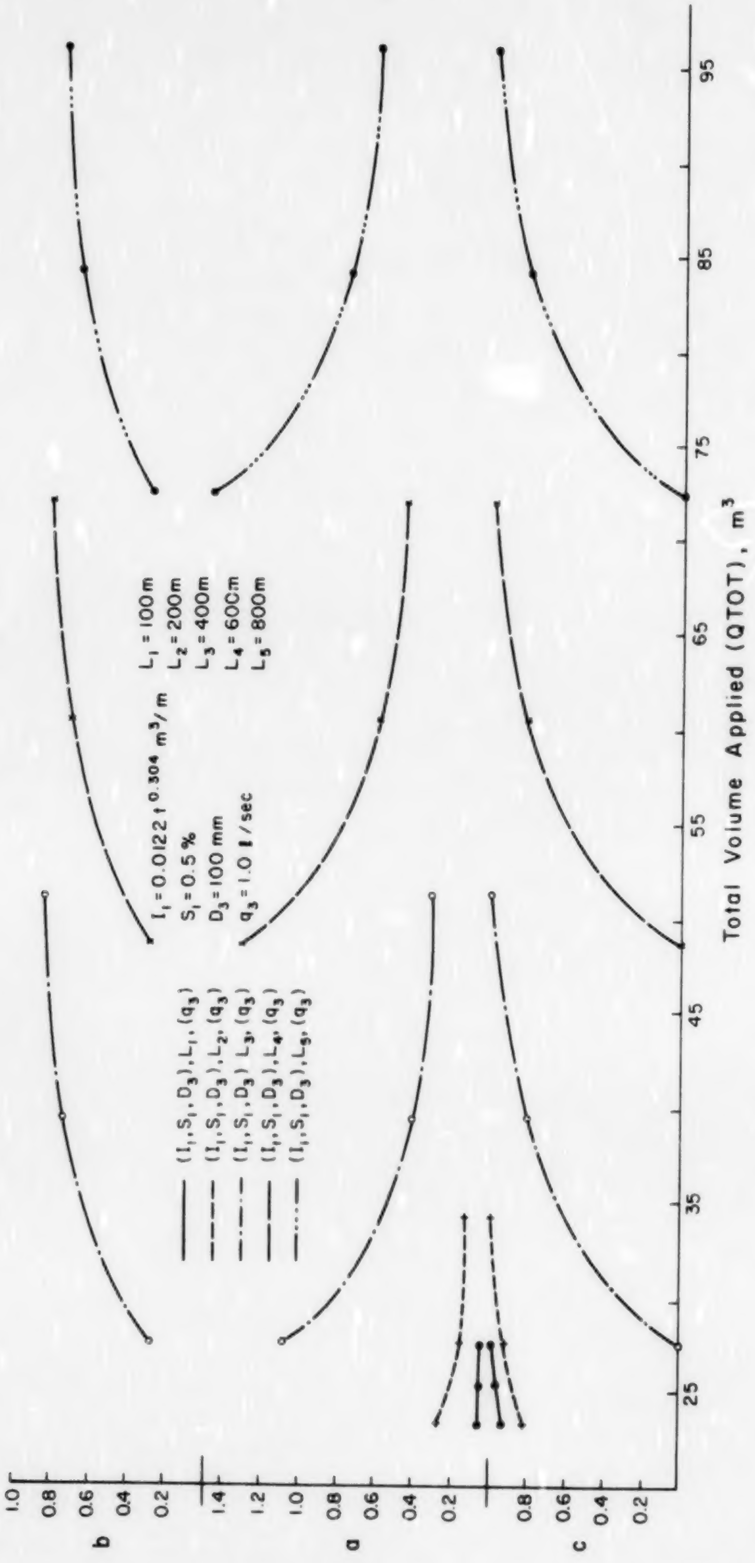

Figure 10b. Variation in distribution coefficients (a, b, c) for varying discharges and total volume (time) applied (QTOT) in surface irrigation.

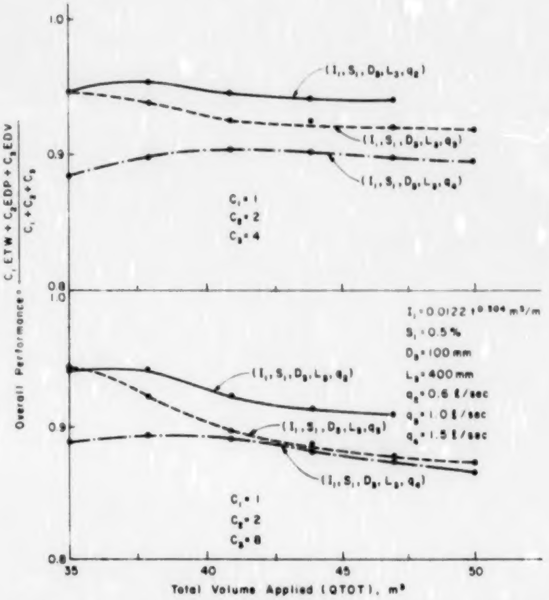

Figure 11. Overall performance as determined by weighted irrigation quality parameters in surface irrigation.

describe the distribution pattern as well as allow for computing efficiencies.

3. Derivation of optimal combinations of distribution patterns and efficiencies with varying design and operation variables such as length of run, inflow rate, desired application depth and total applied volume.

For sprinkler irrigation a single sprinkler pattern may be overlapped in a wide series of feasible alternatives. The results are fitted into a linear regression which allows for assessment of irrigation quality under varying conditions.

Previous studies by Criddle et al. (1956), Wu (1970), Hart (1961), Hansen (1960) and others have suggested various analytical and graphical means to evaluate specific performance parameters.

The results of this study offer a good, efficient and overall means of presenting actual pattern distribution for both sprinkler and surface irrigation systems.

The models suggested allow for integration of the various functions related to irrigation performance such as water-yield function. This is feasible since deviations from optimal depths are established using simple and accurate techniques.

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Hydro-Salinity Models: Sensitivity to Input Variables

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ABSTRACT

Return flows estimated from salinity, or a water budget analysis, exhibit opposite sensitivities to increasing field irrigation efficiencies. However, the sensitivities of both methods to assess return flows may be complimentary if both are used to obtain an optimized estimate of return flows. The degree of data uncertainly would undoubtedly be greater in areas with multiple return flow paths, greater sources of underflows and rainfall, and shorter growing seasons.

Complex methods are being increasingly used to assess the environmental impact of irrigation projects. The development of models that account for the hydrologic and salinity balances of a large agricultural area is a major undertaking. Once developed, the need for answers to a specific set of conditions often precludes a thorough sensitivity analysis of the calculated values based on the expected variability of input data. For example, results of an optimization study by the Bureau of Reclamation showed that shifts in cropping patterns greatly affect the calculated return flows from the Wellton-Mohawk Irrigation and Drainage District in Arizona.

At our laboratory we have been interested in the use of salinity measurements to determine leaching fractions and field irrigation efficiencies in several field experiments. We have also been asked recently to assist SCS in evaluating how much improved irrigation methods may be expected to reduce salt loads of irrigation return flows. In both endeavors the nature and extent of soil salinity variability are important. In the field experiments (U.S. Salinity Lab Staff, 1977), we hope to demonstrate that improved irrigation will reduce salt loading. In the assistance to SCS, we're confronted with the need to assess the magnitude of salt pickup or precipitation under current operating conditions. This conference provided an opportunity to combine our experience with that of the Bureau of Reclamation to assess the sensitivity of volume and salt content of return flows to shifts in cropping patterns and soil salinity variability.

RESULTS AND DISCUSSION

Soil Salinity Variability

Measurements of soil salinity (Oster and Rhoades, 1975; Rhoades, 1976) or *in situ* chloride concentrations provide a means of assessing leaching fractions or field efficiencies of irrigation water use. Chloride is a conservative salt species, since it does not enter into exchange or precipitation reactions. Consequently, the chloride concentration in the soil, C_s, depends upon the concentration in the irrigation water, C_w, and leaching fraction, LF, according to the well-known relationship

$$C_w / C_s \cong LF. \qquad (1)$$

The approximation symbol was used purposely to indicate variations can occur due to several causes: rainfall, changes in C_w with time, or seasonal variation in water management associated with over- or under-irrigation. The C_s can also vary as a result of nonuniform water infiltration or crop water uptake. The variability in C_s, both in magnitude and distribution, is relatively unknown. However, it is understood to be large, and by inference, so is the variability in soil salinity.

Variability of soil chloride concentrations was characterized, based on data obtained from three field experiments that comprise the following irrigation methods, location, soils, crop and soil depths:

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1. Sprinkler and flood.
    a. Grand Valley, Colorado; Ravola loam; corn; 0.60 - 0.90m and 0.90 - 1.20m.
    b. Wellton-Mohawk Valley, Arizona; Indio fine sandy loam; alfalfa; 0.9 - 1.2m and 1.2 - 1.5m.
2. Trickle and flood.
    a. Wellton-Mohawk Valley; Dateland fine sandy loam; citrus; 0.6 - 0.9m and 0.9 - 1.2m.

The arithmetic and geometric means of soil chloride concentration — the latter from log-transformed data — standard deviations, skewness and kurtosis were calculated for each soil depth, crop and irrigation method and, for citrus, by leaching treatment. A separate array was created for each sampling date. If the geometric means for the two depth intervals were not significantly different ($P = 0.10$), the data were combined into a single array. The means of these arrays were then tested against others for the same location. Where possible, they were combined to create the largest possible sets of data. Probability diagrams of the largest arrays for each crop are shown in Figures 1 and 2. For corn and citrus the distributions in Figure 1 are skewed; more than 70% of the chloride concentrations are less than the mean. The curvature is typical of data that is log normally distributed. The coefficients of variation (standard deviation/mean) ranged from 0.6 for alfalfa to 1.0 for corn, which is also typical of data not normally distributed. The log-transformed data, Figure 2, were more normally distributed: the cumulative distribution approached a straight line. The number of observations less than the mean were about 55% and the coefficient of variation ranged from 0.11 to 0.28, which is within normal distributions.

The above distributions were typical of all data arrays, as shown in Figures 3 and 4. These probability diagrams are plotted as a function of the variable $(C_{si} - \overline{C}_{si})/S_i$, where S_i and $\overline{C}_{si}$ are the standard deviation and mean for each array i. Consequently, Figures 3 and 4 represent the general characteristics of all the data. They show that the log-transformed data are more normally distributed than the untransformed data.

The sensitivity of a statistical analysis may be improved by the use of log-transformed chloride data. For example, in our analysis of variance of chloride data obtained beneath a tree canopy, the use of log-transformed data increased the number of significant sources of variation. The standard deviation for transformed data was relatively large, but independent of the mean. For untransformed data, it was approximately equal to six-tenths of the mean. However, the confidence limits about the mean would be about the same. To illustrate, we calculated (Table 1) the confidence limits about the mean for the C_s expected for different LF's when $C_w = 3.3$ meq/l and the sample size (N) is 10. The selected value for C_w corresponds to the chloride concentration of Colorado River water at Imperial Dam. For untransformed data, the upper and lower limits were calculated from the expression,

$$C_w / LF \pm t_{.1}\, S(C_s) / \sqrt{n} \qquad (3a)$$

or

$$C_s \pm 1.84 * 0.6\, C_s / \sqrt{n} \qquad (3b)$$

where 1.84 is the value of t at a probability of 0.1 for 9 degrees of freedom. For transformed data, S was assigned the value 0.25, the average found for all arrays. The antitransformation from log C_s back to equivalent untransformed values was accomplished according to the following equations, (Hald, p. 164, 1952):

$$\text{Upper limit; } \overline{C}_s\, (1 + \alpha), \qquad (4)$$

$$\text{Lower limit; } \overline{C}_s \,/\, (1 + \alpha), \qquad (5)$$

$$_{10}\log \alpha = t_{.1}\, S/\sqrt{n}\,. \qquad (6)$$

Both log-transformed limits are slightly higher than the untransformed limits. The upper limit is increased because of the abnormally large number of high concentrations in the distribution of concentrations about the mean; the lower limit, because the mode of the distribution is somewhat less than the mean. For practical purposes, the two values for the upper and lower limits are the same. Even though the limits calculated from transformed and untransformed data differ little, their theoretical interpretation differs significantly. No valid statement can be made about the probability levels of the confidence interval calculated in the untransformed case. The transformed data closely approximate a normal distribution, so that valid probability statements are possible.

Although the difference between the upper and lower limits increases with decreasing leaching fraction. The confidence intervals about the leaching fractions determined from average chloride concentrations decrease with decreasing leaching fraction or increasing field efficiency of water use. The data in Table 1 were converted to irrigation efficiencies, E, according to

$$E = 1 - LF = 1 - C_w / C_s. \qquad (7)$$

Upper and lower limits of E were calculated by using the corresponding limit values for C_s. The results are illustrated in Figure 5. The confidence interval becomes smaller with increasing efficiency because of its inverse dependence on C_s. Consequently, for low field efficiencies of 0.4 to 0.6, the likely error in irrigation efficiencies calculated from chloride data would be relatively large and so would the error in predicted return flows.

Improvements in irrigation efficiencies from 0.45 to 0.6 are commonly projected in study plans being prepared as a result of the Colorado River Basin Salinity Control Act (PL 93-320). If these are representative of field irrigation efficiencies, then chloride measurements apparently would not be useful in evaluating the consequences after implementing improved practices. At efficiencies above 0.8 the level of confidence would be greatly improved.

Projections of mass emissions of salt from irrigated projects based on soil salinity measurements would be subject to a similar uncertainty. Mass emissions of chloride, Figure 6, were calculated from the log limits in Table 1 from the equation

$$\text{MASSCl} = C_s D_p = C_s * A * C_u (1/E - 1) = C_s * A * C_u \left[\frac{C_x}{C_s - C_w} \right] \qquad (8)$$

where D_p represents deep percolation. Area, A, was assigned a value of 1ha and consumptive use, C_u, was assigned a value of 1500 mm. Obviously, at irrigation efficiencies of 0.5 the degree of uncertainty would be very large; however, at efficiencies of 0.8, soil salinity measurements would be a sensitive measure of mass emissions.

Return Flows — Crop and Water Data

The water budget for an area is the standard method used to estimate the volume of return flows from an irrigated field or irrigation district. Deep percolation from irrigated fields is often a major component of irrigation return flows. Water use efficiency varies from crop to crop because of different cultural practices. Consequently, the sensitivity of a water budget analysis to different cropping patterns is of interest.

The Yuma office of the Bureau of Reclamation recently reported the results of a sensitivity study[1] of the Wellton-Mohawk Irrigation District. This district is relatively simple hydrologically; irrigation return flows are confined to a closed aquifer, which is pumped to maintain satisfactory water table levels; underflows and rainfall are small, about 4% of the diversions; and return flows from the lined canals and consumptive use by phreatophytes are each estimated to be about 10% of the diversions.

A linear optimization procedure was used to perform the sensitivity analysis. Crop input data included a 6-year (1970-1975) compilation of actual irrigated areas by crop. The cropping patterns of the 15 crops grown in the district were modeled with 17 equations, one for each month and five additional equations to account for midmonth cropping pattern changes. Each equation represented the total area of irrigated crops. In the optimization procedure, bounds were placed on the total and individual crop areas so that they remained between 6-year maximum and average areas. For a given set of efficiencies, individual crop area was optimized to obtain estimates of maximum and minimum return flows, D_p, according to the relationship,

$$D_p = \sum_{i=1}^{15} A * CU * [1/E_i - 1], \qquad (9)$$

where i represents an individual crop.

The results given in Table 2 for one set of efficiencies show that deep percolation can vary considerably depending on the farmer's choice of crops to be grown. At program level 1, which represents a minimum level of improvement, it varied from 0.132 to 0.175 km^3. Deep percolation was maximized as a result of increased areas of cotton, lettuce, melons, wheat and sorghum. The area of these crops were least constrained because they can be grown in rotation with others: 1) cotton, wheat and sorghum in rotation with lettuce and barley, and 2) wheat in rotation with sorghum, cotton, and melons.

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[1] Measures for Reducing Return Flows from the Wellton-Mohawk Irrigation and Drainage District, 1976 Annual Report, Technical Field Committee, Yuma Projects Office, Bin 5569, Yuma, Arizona, 85364.

Cropping patterns significantly affect deep percolation from fields for different sets of overall crop efficiencies (Fig. 7). Under the cropping pattern for 1974-1975, deep percolation ranged from 0.192 to 0.249 km^3 and for irrigation management improvement level 3 efficiencies it changed from 0.102 to 0.142 km^3. Figure 7 also shows estimated return flows for the total system, which include losses due to canal seepage and consumptive use by phreatophytes and gains due to rainfall and underflows. The variation because of different cropping patterns, A, is a major component of that for the total system, B $(.48 > A/B < .71)$. The relative uncertainty in estimated return flows for the total system increases from 18 to 32% $[100 * .5B/(.5B + D)]$ as efficiency increases from current levels to those projected for level 3. In other words, the more efficient the irrigation system, the greater the relative error associated with estimated return flows; the largest single component of uncertainty is a shift in cropping patterns.

CONCLUDING COMMENTS

Return flows estimated from salinity, or a water budget analysis, exhibit opposite sensitivities to increasing field irrigation efficiencies. The former depends upon a ratio where, at lower efficiencies, a small variation in a small number results in a large change. At high efficiencies, the larger numbers assure a small ratio with little dependence on variability. The sensitivities, at low efficiencies, for water budget data depend on relatively small changes in large numbers. The situation reverses at high efficiencies; the water input is decreased, whereas the consumptive use and its uncertainty remains fixed. The sensitivities of both methods to assess return flows may be complementary if both are used to obtain an optimized estimate of return flows.

Salinity or chloride variability would be dependent upon the volume of soil sampled. The data we presented was based on a soil volume of about 9×10^{-5} m^3 (3 cm^2 $\times$ 30 cm). This variability would not apply to drainage tile effluents; the effective volume sampled could approach 2×10^4 m^3 (400m x 30m x 3m). Such a sample integrates the variability over space as well as time. The variability would be smaller, but the concentration measured would be more difficult to interpret. The variability of soil salinity measured using resistivity techniques would be intermediate because the sample volume is about $1 m^3$.

Time of sampling is another variable we have not considered (Jury, 1975; Raats, 1977). It certainly is one limitation with regard to the usefulness of salinity or individual ion concentrations to estimate return flows or mass emissions. The lag time between imposition of management changes and resulting change in soil solution or effluent concentrations would increase with increasing efficiencies. Long-term decisions based on short-term measurements could result in serious errors.

The sensitivity data we have presented probably are conservative. The chloride data were obtained from soils irrigated for many years. The variability in unirrigated soils in the West could be even greater. The Wellton-Mohawk area represents a relatively simple hydrologic system. The degree of uncertainty would undoubtedly be greater in areas with multiple return flow paths, greater sources of underflows and rainfall, and shorter growing seasons.

One objective of the presentation is to raise several questions about the uses of large-scale models: 1) Is it realistic to attempt large-scale verification? 2) What constitutes proper use of models quantitatively or to predict trends? 3) Should we increase the efforts in sensitivity analyses on more systems? The last question may be the key. If more were known about the sensitivity of model output to the variability of

TABLE 1

Ninety percent confidence interval of mean soil chloride concentrations where the chloride concentration of the irrigation water is 3.3 meq/l and n = 10.

		Untransformed			*Log transformed*		
		Stand.	*Limits*		*Stand.*	*Limits*	
Leaching Fraction	C_s (C_{iw}/LF)	*Dev.*	*Upper*	*Lower*	*Dev.*	*Upper*	*Lower*
	meq/l						
0.6	5.5	3.0	7.2	3.8	.25	7.7	3.9
0.5	6.6	4.0	8.9	4.3	.25	9.2	4.7
0.4	8.2	5.0	11.1	5.3	.25	11.4	5.9
0.3	10.0	6.0	13.5	6.5	.25	13.9	7.2
0.2	16.5	10.0	22.3	10.7	.25	23.0	11.8
0.1	33.3	20.0	44.9	21.7	.25	46.4	23.8
0.05	66.0	40.0	89.1	42.9	.25	92.1	47.3

input variables, it might be possible to formulate more definitive answers.

TABLE 2

Deep Percolation from Farms — Reflecting various levels of efficiencies, historical crop data and Acreage reduction.

Crop	Crop Cu. (mm)	Program Level I. Minimum Irrigation Efficiencies			Program Level I. Maximum Irrigation Efficiencies		
		Area (ha)	Eff.	Deep Perc (km³)	Area (ha)	Eff.	Deep Perc (km³)
Alfalfa	1830[1]	9206	78	0.0475	9112	79	0.0443
Pasture	1040[1]	870	52	0.0083	870	64	0.0051
Cotton	1070	4302	79	0.0122	3694	79	0.0105
Safflower	1160	257	77	0.0009	257	77	0.0009
Lettuce	240	3532	25	0.0258	1450	25	0.0106
Melons	488	1264	37	0.0105	239	37	0.0020
Wheat	670	5868	70	0.0169	5205	70	0.0150
Barley	640	60	70	0.0002	141	70	0.0004
Sorghum	670	3874	63	0.0152	1525	63	0.0060
Leaching	30	139	5	0.0008	58	5	0.0003
Misc.	580[2]	661	44	0.0049	661	44	0.0049
Bermuda G.	980[1]	2673	70	0.0112	2673	70	0.0112
Grapefruit	1220	75	40	0.0014	75	40	0.0014
Lemons	1280	324	40	0.0062	324	40	0.0062
Oranges	1000	858	40	0.0129	858	40	0.0129
TOTALS		33962	67	0.1748	27141	70	0.1315

[1] Consumptive use reduced to estimate incomplete growth cycles for a portion of these crops which are normally in rotation each year.

[2] Consumptive use estimated to reflect expected miscellaneous crops obtained from historical crop data.

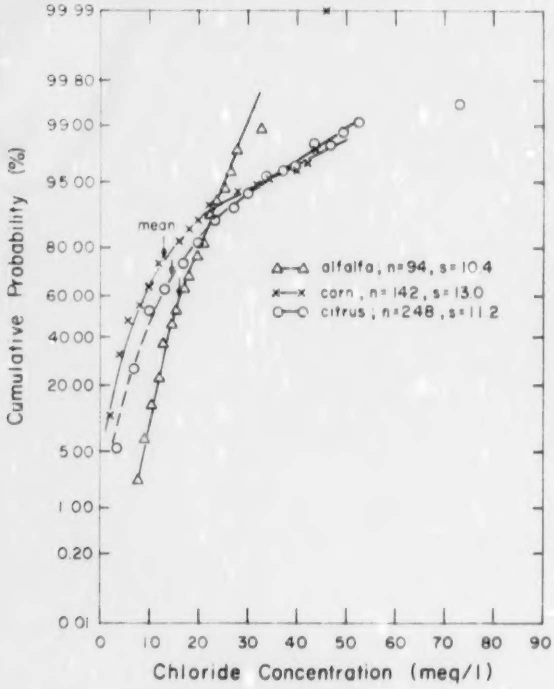

Figure 1. Cumulative probability untransformed chloride concentrations. S represents the standard deviation.

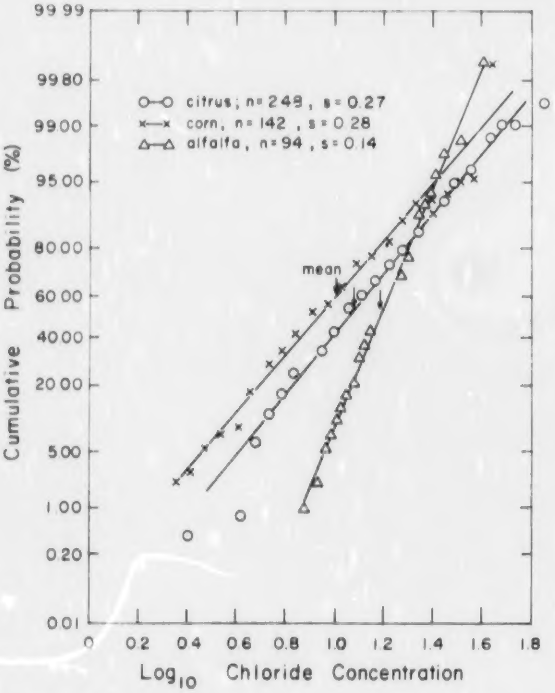

Figure 2. Cumulative probability for transformed chloride concentrations.

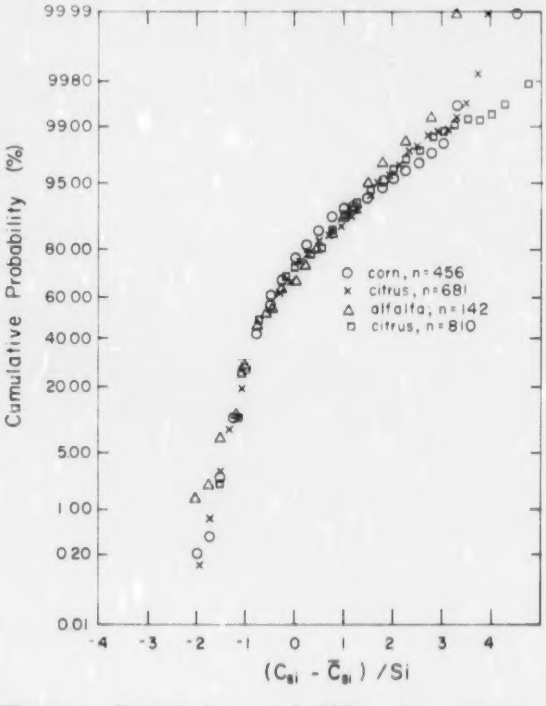

Figure 3. Cumulative probability for untransformed, reduced chloride concentrations.

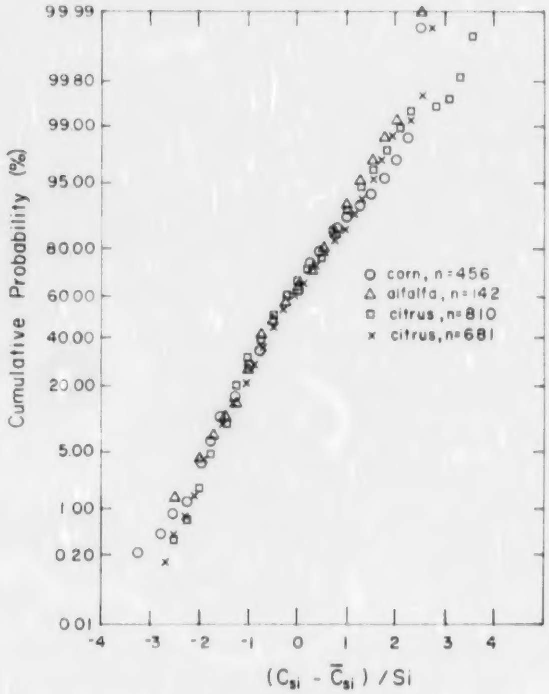

Figure 4. Cumulative probability for transformed, reduced chloride concentrations.

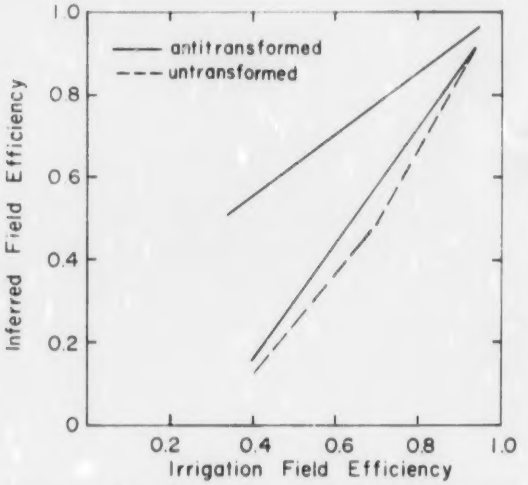

Figure 5. Confidence intervals for inferred field efficiencies. Calculated from transformed (P = 0.10) and untransformed chloride data assuming a sample size of 10.

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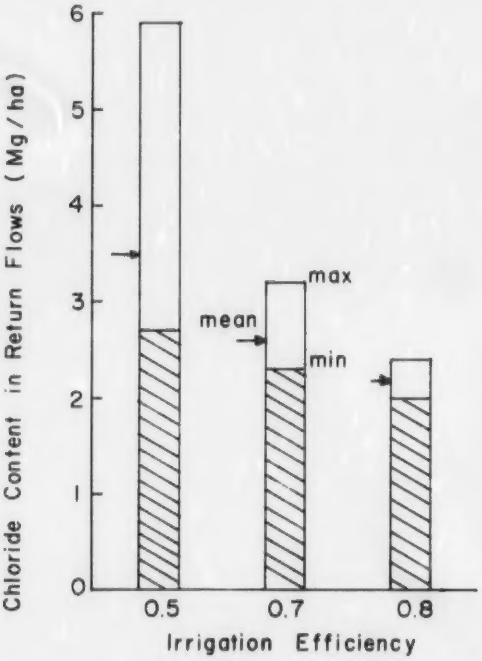

Figure 6. Confidence intervals, (P = 0.10) for chloride content of irrigation return flows of different levels of field irrigation efficiencies.

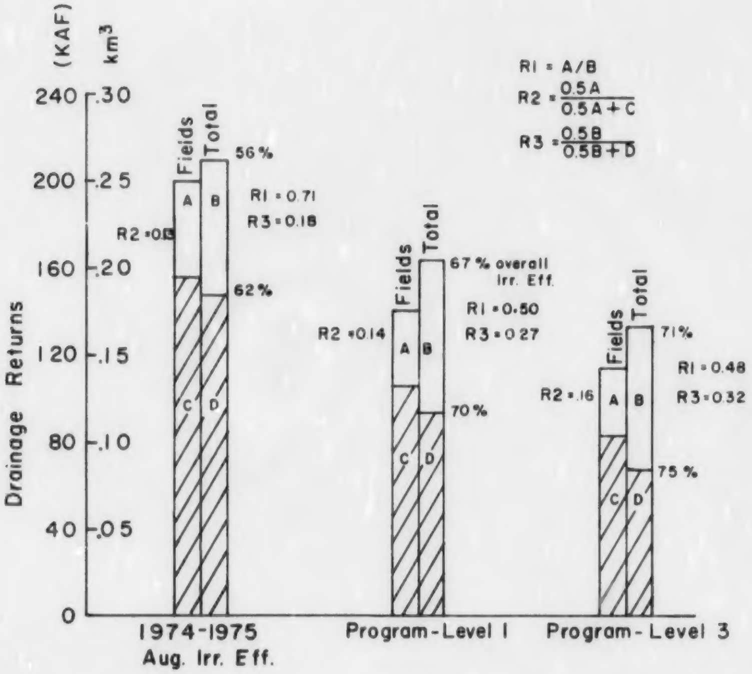

Figure 7. Maximum and minimum drainage returns with acreage reduction for various efficiency levels for irrigated fields and for the total Wellton-Mohawk Irrigation and Drainage District.

Modeling the Irrigation Return Flow System — Current Capabilities and Future Needs

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ABSTRACT

A large number of mathematical models have been developed and tested for simulation of irrigation return flow systems. The strengths and weaknesses of the technology have been examined as part of two recent studies by the author. This paper discusses what seems to be some of the more critical problems in using these models, the relative strengths of those existing, and important research and development needs for maximizing their utilization in the future.

INTRODUCTION

Return flows from irrigated agriculture generally contain at least some concentrations of salts, nutrients, pesticide residues, and sediments. Each of these "pollutants" can have adverse effects on the future benefical uses of receiving waters. Measures to diminish the impact of irrigation return flows must be evaluated in terms of their cost-effectiveness, effects on crop production, and the magnitude of the detriments they create.

Mathematical simulations, generally computer based, have become the tools utilized to evaluate both the irrigation return flow system and alternative means for its control. The existing body of these "models" is comparatively large, which might be attributable to a number of factors including: (1) the broad and complex scope of the irrigation return flow system; (2) the large number of both scientific disciplines and researchers interested in one phase or another of the problem; and (3) model duplication.

In the last few years, the author has been collecting the various irrigation return flow models and recently evaluating their characteristcs. Listings from about 1/2 to 2/3 of the more than 50 available models have been obtained and examined. This paper is intended to briefly summarize some general thoughts regarding this experience.

The actual beginnings of my effort occured during March of 1975. A three-day workshop was sponsored by the Environmental Protection Agency which involved ten participants, the author, and EPA Project Officer, Dr. Arthur G. Hornsby. Eight of the workshop group are participating in the papers or case study presentations at this conference. Those present by no means represent an exclusive body of modelers, but were selected to sample the various research and administrative concerns. The workshop involved three phases: (1) discussions concerning modeling philosophy; (2) presentations of various modeling activities; and (3) examination of the recent modeling efforts within the Bureau of Reclamation. Two of the most interesting results from the workshop were the opinions generated in regard to modeling philosophy and the pertinent research needs for improving this technology. After the workshop had been evaluated, another small project was funded by the Environmental Protection Agency to collect and evaluate the various models available.

Space does not permit an exhaustive review of the available models nor an in-depth look at their capabilities. Instead, the writer would like

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to briefly summarize a number of issues that have been raised in order to place a perspective on today's irrigation return flow models.

PROBLEMS IN MODEL UTILIZATION

A simulation model is generally a set of mathematical relations applied to approximate boundary conditions that attempts to simulate the relationships between variables in the natural system. It is useful in understanding the natural system and in evaluating its behavior under proposed management alternatives. Researchers have been prolific in applying modeling concepts to the various segments of the hydrology in an irrigated area.

A number of modeling efforts have been reported with various degrees of modification in the work of others, but the most prevalent practice is to develop a model for the specific purpose at hand. Consequently, irrigation return flow models of all kinds are somewhat individualistic in nature, each tending to express the modelers perception of a problem solution, rather than a more generalized approach simplified to a particular need.

The use of existing irrigation return flow models pose some severe problems. First, an investigator or planner is almost always faced with analysis of problems extending beyond the limits of his own expertise. Thus, at least some part of most modeling efforts involve computations which must be "trusted." However, cases occur when models are improperly utilized because the assumptions governing the original formulation are no longer valid. Furthermore, even when the assumptions are explicit (which is not the general case), the untrained user may not know whether the assumptions are valid or not. It is, of course, the responsibility of the model users to insure the applicability of a model, but the model developer must also be charged with defining the limitations of the model.

A second major problem in using existing models is the variability in programmer skills and computer languages. One of the ironic concepts encountered in using computers is the notion that efficient coding is cost-effective. Modern computers are so rapid in their internal operations and software manipulations that the difference between the expert and novice in programming for a particular need is orders of magnitude less than personnel costs, especially in the agricultural and engineering disciplines. In fact, research budget categories allocated to computer utilization probably never exceed 5-10% of the total research costs. Consequently, the disadvantages in simpler programming with respect to cost are probably more than offset by the added ease in adapting to other computers and utilization by a wider audience. For example, most agricultural and engineering students only become familiar with the Fortran language so that use of other language packages such as CSMP (for IBM computers) may significantly limit the utilization of the model.

In examining the models of others, and doing substantial modeling myself, the conclusion appears to be that very few major computer codes are verified, or in other words, checked to determine if they actually make a calculation according to the intended format. Even the most expert programmers misplace parentheses or improperly nest indexes and counters. If the generated results appear reasonable, then the code is considered correct; otherwise, the specific problem is amended. Occasionally, problem solutions involve a small fraction of the loops and branches found in a program so that some unused program routes are not always checked. When another user tries to employ the model under different conditions where other program segments are used, a great deal of difficulty may be experienced with the program. Models should be verified against computations made outside the computer code.

Irrigation return flow models available today occasionally contain segments having vastly different sensitivities in their simulation of various elements of the system. Many of the soil physics and chemistry models were developed under concise laboratory conditions where data quality is controlled within reliable limits. When these models are coupled with hydrologic models developed for field scale applications, a significant disparity exists in refinement. Data at the field scale are highly variable so that in using detailed models the necessary assumptions may render them no better and probably worse than more simplistic approaches.

And finally, there is often a tendency to place too much credibility on the output from a computer simulation. The irrigation return flow system is very complex. In fact, many of those complexities are only marginally understood. As a result, simulation models are nearly always empirical to some extent, and therefore are at best, tools to assist the investigator. They are not, however, instruments for verifying extended hypotheses as is the case when conclusions are drawn from extensive output based on questionable or poor data.

CURRENT CAPABILITIES

During the 1975 modeling workshop, a number of the segments of the irrigation return flow system were thought to be reasonably well simulated with existing models. This opinion of course is in the relative sense in considering the irrigation return flow models as a whole. The examination of the various available models since the workshop has generally substantiated the earlier expressions.

Of the irrigation return flow system models, probably the best developed for field scale applications are the evapotranspiration-irrigation scheduling models. Evapotranspiration estimating procedures have been developed for a wide variety of data availabilities, although irrigation scheduling is generally limited to two or three of the more inclusive methods. The weakness of these models is that they are primarily limited to predicting early growth water demands and the effects of stress on use rates.

The flow of water after entering the soil is also well modeled with existing programs. Recent developments in regards to two- and three-dimensional flow predictions have broadened the scope of this area of irrigation return flow models to encompass all of the irrigation system varieties. Unsaturated flow models of both transient and steady-state conditions can be found in numerous places throughout the literature. Most of these models, however, do not include terms to account for moisture extraction by growing crops, and the boundary conditions assumed for surface water applications are occasionally unrealistic in the true physical sense. The most severe constraints in using these models lie in characterizing soil hydraulic properties since such data are not generally available from one location to another.

Chemistry predictions associated with unsaturated flow are relatively well developed for the basic components of salinity. Some pesticides and volatile constituents like the nitrogen species are much more complex and therefore less accurately modeled. Again, respesentative field data pose the more rigid restrictions on the reliability of these models. A number of soils contain naturally occurring salts that are dissolved by flows passing through the unsaturated zones (salt pickup effects). Most models do not handle this condition, although some of the more recent modeling studies in Utah have considered the problem by adding sink and source terms to existing models.

Moisture and chemical flows in the saturated regions can be simulated with reasonable accuracy whenever data are available and the physical nature of the hidden system can be ascertained. Unfortunately, most areas have very little groundwater data. In irrigated fields underlain by drainage systems, the model capabilities are reasonably good since verification has been possible during model development.

These areas of irrigation return flow modeling represent the best developed segments of the modeling topic, but they consider only individual processes in the system. On a more integrated scale, there exist a number of general hydro-chemical models which include, to some degree at least, the various processes present. These models generally have expanded time (one-week to one-month) and spatial (one-ha to several thousand ha) reference frames and therefore predict the distribution of the average conditions. These models also considered very simplistic simulations of the detailed hydro-chemical processes because large scale data resolution is very poor. However, in those cases where verification has been possible, predictive capability has often been comparable to more detailed analyses.

A final group in the modeling technology is the models which utilize simulation results in management and optimizational contexts. Very few if any such models exist with enough generality to allow widespread utilization by others, and in fact, this area of modeling is almost exclusively a philosophy and "art" oriented effort, primarily because of the totally site-specific nature of problems at this level of investigation. The science utilized in such modeling efforts is extremely well developed and proven even though structuring problems in the "systems analysis" format is generally a skill.

FUTURE NEEDS

The future needs in irrigation return flow modeling can be broken down into two areas: (1) research and development needs; and

(2) needs in regards to disseminating existing models to the user community.

Irrigation return flow models have developed over the last few years at three distinct levels. First, what might be called process level models which are limited in scope to a single hydro-chemical process. These models have been written at the most basic level, justified by existing information. However, a specific process might have been modeled at various levels of sophistication depending on the requirements of its use and available data. Simulation of cropland evapotranspiration is a good example of the typical process model. In its most refined forms, the crop use rates are determined by a relationship like the Penman combination equation. Other simple versions may use pan evaporation, Jensen-Haise, Blaney-Criddle, etc., depending on data and intent. Other process models include such processes as unsaturated flow and associated chemistry. Among the process level models, there are several important research and development needs. Those include: (1) improved simulation of irrigation water application uniformities as influenced by system design and operation; (2) evaluation of the impact of irrigation frequency and timing on root zone water and chemical flows; (3) improved simulation of nitrogen transformations in irrigated soils; (4) improved simulation of root extraction of moisture and nutrients, particularly the depth distribution of the extraction pattern; (5) investigation of crop growth-stage and stress coefficient for estimating early season evapotranspiration; and (6) evaluation of unsaturated soil chemistry predictions when large quantities of natural salts are present in irrigated soils.

The second level of model development might be termed the subsystem level representing a combination of various process models capable of simulating a major part or all of the irrigation return flow system. For instance, subsystem models can be fabricated to examine in various degrees of detail the region between the soil surface and water table. Process models would include irrigation uniformity (including infiltration), evapotranspiration-root extraction, unsaturated flow and unsaturated chemistry. A sampling of the opinion of the earlier workshop participants indicated that most potential model users involved in research would prefer to develop their own subsystem level models to meet the specification of scope and detail associated with their problem. One must suspect, however, that the planner or consultant would prefer the system level model since they may not be comfortable synthesizing process level models which may be only vaguely understood. Consequently, an important future need concerns the sensitivity of these models to various kinds of input data. In other words, for subsystem level models with varying degrees of sophistication and varying time and spatial resolutions, which data must be most carefully considered? In addition, the conditions under which these models can and cannot be applied should be clearly delineated.

The third modeling level is the hydrologic and irrigated system model which includes the irrigation return flow system as a subprogram, or as the entire program treated at a "macro" level. These models tend to large area, large time averaging systems, predicting on an input-output basis. They are generally comprised of the more simplistic process simulations and subsystem level programs since their time and spatial resolution usually do not justify more sophisticated programs. And, large scale data are generally poor and few. Further needs in respect to these models may be more oriented to evaluation of how well sampling data represent field conditions, although parameter sensitivity analysis and assumption validity remain critical.

One of the interesting results of the workshop alluded to earlier was that most of the participants did not believe information regarding the various irrigation return flow models was generally available, particularly with regard to operational instructions. Most of the participants felt that very little information was being published relative to the sensitivity of model parameters and results as affected by various kinds and qualities of input data. Consequently, the majority of models are not utilized by other than the authors and a few associates, especially by those in other disciplines. Thus, an important future need is to collect the various computer programs available, simplify their codes in order to maximize their adapability to the wide range of computers being utilized, and make the programs available to potential users with sufficient instructions to facilitate their use in the proper manner. After this step, it might be useful to develop a more consistant or uniform program library by reprogramming those already existing models and adding models, where research findings have added to modeling capabilities.

The irrigation return flow modeling system is readily applicable to many other problems associated with the irrigation of agricultural lands. Many of the models are already being utilized to increase irrigation efficiency, evaluate organic waste disposal practices, maximize crop production, and conserve energy, fertilizer, and water resources. It appears that our current model capabilities are sufficient for most needs although hard to apply and uncertain to interpret. A few simple steps in our future work should go a long way in improving these capabilities.

Case Studies

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Application of Modern Irrigation Technology in the Mesilla Valley, New Mexico

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ABSTRACT

Current engineering technology is being applied to a Demonstration Farm in the Mesilla Valley, New Mexico to demonstrate the feasibility of decreasing the large amount of salt returned to the Rio Grande River System through return-flow drainage. The reduction in return flow is accomplished by irrigation scheduling techniques and more-efficient irrigation methods, such as drip irrigation. A small pecan orchard has been converted from flood irrigation to drip irrigation resulting in the water application reduction greater than 50 percent with a marked visible increase in growth rate over that of the previous year. Irrigation scheduling increased the efficiency of irrigation timing on the farm resulting in an improved soil condition, in some cases one less irrigation. Monitoring of the applied water on the Demonstration Farm resulted in estimates of irrigation efficiencies for the season ranging from 54 percent for wheat to 97 percent for alfalfa. The high efficiency for alfalfa was probably due to the high water table which contributed water to the crops in addition to the applied water. Monitoring of the soil salinity is enabling the investigators to follow the movement and buildup of salt below the root zone with increased irrigation efficiencies. Information gained from the Demonstration Farm is being used by the Cooperative Extension Service in an educational program. The various methods used to make the public aware of EPA's efforts on the Demonstration Farm include media releases, tour brochures, and field days.

INTRODUCTION

Current engineering technology is being applied to a 182-hectare Demonstration Farm in the Mesilla Valley, New Mexico to show the feasibility of alternative water-management practices on the quality of drainage return flow and soil salinity in the Upper Rio Grande Basin. The crops grown on the farm are: wheat, tomatoes, cotton, lettuce, tobasco peppers, chile peppers, alfalfa, and a pecan orchard. The source of the irrigation water is Rio Grande water from the Elephant Butte Irrigation District augmented by wells installed at various locations throughout the farm.

Figure 1 presents a map of the farm with the irrigation distribution system and the associated hectares under production for each crop. Because of the deep drainage problem that exists in the valley, drains have been installed to maintain the water table at a depth of 2-2.5 meters.

METHODS

To improve the farm irrigation efficiency for the various crops, it was necessary to measure the water by installing meters on all of the irrigation pumps, and Parshall flumes in all the irrigation ditches receiving surface water. A complete record was kept of the water applied from both surface and groundwater sources on each of the fields.

Rain gauges were installed at the Demonstration Farm and the New Mexico State University Plant Science Farm to measure the precipitation in the area; however, the mean annual precipitation averages less than 25 cm with most of the rain falling in the summer from thunder showers caused by tropical air masses coming in from the Gulf of Mexico. Essentially all the consumptive-use requirements of the crops are satisfied by irrigation.

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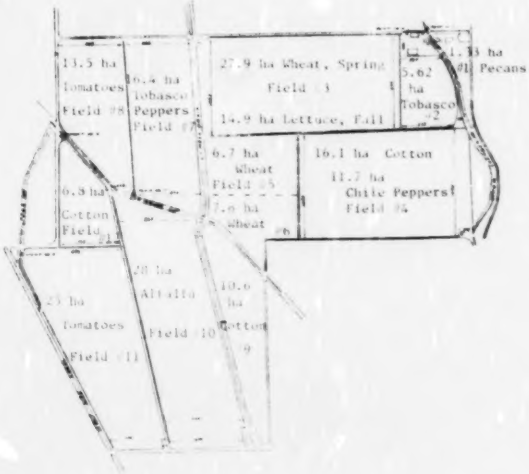

Figure 1. A map of the crops grown on the EPA Demonstration Farm in the Mesilla Valley.

Flow rates and water qualities were monitored in the La Mesa Drain passing through the center of the farm in order to establish the amount and quality of the return flow from the surrounding area. Piezometer wells monitored the groundwater fluctuations.

To implement the objective of the demonstration project, 1.33 hectares of pecans were converted from flood irrigation to drip irrigation. In the process of converting the orchard to drip irrigation, a well was installed to provide clean, good-quality water for irrigation and domestic uses. An automatic back-flushing sand filter was installed to supply the necessary filtration required to operate a drip irrigation system.

An irrigation management schedule service is being provided to the farm for scheduling irrigations based upon the estimated consumptive use of the crops and the available moisture within the root zone (2). The consumptive use is estimated by a computer model using micrometeorological data. Prediction is made on the estimated consumptive use in the future. When the available soil moisture has been depleted by 50%, irrigation is scheduled. The information is checked weekly in the field and the model updated continously to account for the changes in the micrometeorology. Using this approach, the timing of the irrigations are as close to optimum as is practical. Information about the daily consumptive-use rate on several crops has never been determined for the conditions in this valley. Under these circumstances, the irrigations were scheduled based upon soil moisture availability measurements made in the field.

RESULTS AND DISCUSSION

Table 1 presents the irrigation date of applied water, and the estimated consumptive use for that time period for each field on the Demonstration Farm. The table also presents the information on the percentage of water supplied by surface vs. groundwater ranging from 36% surface water for the tomato fields to 87% for the cotton fields. The farm, on an average, received 69% of its water from the Elephant Butte Irrigation District and the rest from pumped groundwater. The seasonal irrigation efficiency, based upon the consumptive use divided by applied water without considering rainfall, ranged from 54% for one of the wheat fields to 97% for the alfalfa fields. The alfalfa evapotranspiration was measured ina lysimeter nearby. The cotton and wheat evapotranspiration rates were determined from the Jensen-Haise method (1). Because of the shallow water table, the alfalfa roots were able to extract moisture from the groundwater system. If the amount used from the water table was added to the applied surface water, the computed efficiency would be less. The average farm irrigation efficiency, using the service of irrigation scheduling, was 72%. The variability in the seasonal irrigation efficiency from field to field growing the same crop was due, in part, to how closely the irrigations were supplied to the field compared to the dates recommended by the irrigation scheduling. Irrigation efficiencies between fields growing similar crops were similar for the tomato and wheat fields but varied for the cotton and pepper fields.

Data on the amount of applied water to the pecan orchard using the drip irrigation system is given in Table 2. The seasonal amount of applied water, spread over the entire 1.33 hectares, for the growing season was 21.6 cm. This is considerably less than would be applied by a surface-irrigation method estimated to be 60 to 80 cm, based upon 6 to 8 irrigations applying 10 cm per irrigation. The low application rate supplied by the drip system is made possible because the emitters only wet a small area around the trees.

TABLE 1

Irrigation water application, source of water, and evapotranspiration for crops on the EPA Demonstration Farm, 1976.

Irrigation Date	Recommended Irrigation Date	Total Water Applied (km³)	Application Per Hectare (km³/ha)	Source of Water	Evapotranspiration (ET) for time period (km³/ha)
Alfalfa-Fd. 10					
3-15-76	3-17-76	46.34	1.643	S[a]	1.040
5-18-76	5-13-76	25.02	.883	G[b]	2.011
6-3-76	6-8-76	72.34	2.556	G	.999
6-22-76	6-24-76	65.86	2.343	-	1.265
7-12-76	7-10-76	57.31	2.039	S	1.420
8-7-76	8-5-76	32.50	1.156	S	1.750
8-20-76	8-21-76	37.63	1.339	S	2.790
9-19-76	9-18-76	37.63	1.339	S	3.398
10-8-76	10-7-76	41.91	1.491	S	.776
Season Total		416.54	14.789		14.151
Percentage Surface Water		60.7%			
Seasonal Field Irrigation Efficiency		95.6%			
Cotton-Fd. 4 West					
3-27-76	pre-irrigate	39.93	2.465	S	
5-12-76	NI[c]	15.41	.943	G	.139
6-28-76	6-30-76	17.99	1.126	S	.766
8-5-76	7-31-76	16.28	1.004	S	2.059
8-17-76	8-22-76	13.19	.882	S	.652
8-28-76	9-2-76	12.94	.791	S	.596
10-27-76				-	1.778
Season Total		115.73	7.151		5.990
Percentage Surface Water		87%			
Seasonal Field Irrigation Efficiency		84%[d]			
Cotton-Fd. 9					
3-29-76	pre-irrigate	24.65	2.313	S	
5-18-76	NI	9.86	.913	S	.185
6-22-76	7-1-76	15.61	1.461	S	.538
8-7-76	8-5-76	12.37	1.156	S	1.149
8-27-76	finished	21.07	1.948	G	1.310
10-5-76				-	2.392
10-27-76				-	.423
Season Total		83.56	7.791		5.997
Percentage Surface Water		75%			
Seasonal Field Irrigation Efficiency		77%			
Cotton-Fd. 12					
3-19-76		5.02	.735	S	
5-13-76	NI	5.18	.761	S	.177
6-29-76	7-1-76	6.83	1.004	G	.766
7-25-76	7-22-76	6.83	1.004	S	1.347
8-21-76	8-26-76	6.20	.913	S	1.544
8-26-76		6.42	.943	G	.294
9-29-76				-	1.296
10-27-76				-	.573
Season Total		36.48	5.360		5.997
Percentage Surface Water		63%			
Seasonal Field Irrigation Efficiency		112%			
Wheat-Fd. 3					
1-13-76	--	40.87	1.463	G	.005
3-14-76	3-17-76	41.90	1.491	S	.477
4-7-76	4-8-76	42.52	1.522	S	.870
4-29-76	4-27-76	42.89	1.534	S	.766
5-13-76	5-12-76	26.25	.938	S	.583
7-12-76	harvested			-	1.164
Season Total		194.43	6.948		3.865
Percentage Surface Water		79%			
Seasonal Field Irrigation Efficiency		55%			
Wheat-Fd. 5 & 6[e]					
1-28-76		19.23	1.461	S	.005
3-26-76	3-26-76	15.41	1.156	S	.872
4-22-76	4-23-76	35.00	2.647	S	.941
5-18-76	5-16-76	22.17	1.674	S	1.144
6-16-76	harvested			-	.817
Season Total		91.81	6.938		3.779
Percentage Surface Water		100%			
Seasonal Field Irrigation Efficiency		54%			
Lettuce-Fd. 3					
8-8-76	none	41.04	2.739	S(52%)	
8-26-76		32.66	2.191	S(37%)	
9-27-76		31.79	2.100	S(68%)	
10-13-76		14.67	.974	G	
Season Total		120.16	8.004		4.514[f]
Percentage Surface Water		46%			
Seasonal Field Irrigation Efficiency		56%			

TABLE 1 continued

Irrigation Date	Recommended Irrigation Date	Total Water Applied (km³)	Application Per Hectare (km³/ha)	Source of Water	Evapotranspiration (ET) for time period (km³/ha)
Tomatoes-Fd. 8					
3-20-76		23.41	1.735	S	
3-23-76		27.73	2.049	S	
5-1-76	5-1-76	19.72	1.461	S	
5-7-76	5-7-76	6.53	.484	S	
6-17-76	6-13-76	10.23	.761	S	
7-13-76	7-10-76	11.95	.883	S	
8-4-76	8-2-76	14.82	1.095	G	
8-20-76	finished	1.64	.122	G	
Season Total		116.03	8.590		5.782[g]
Percentage Surface Water		85.8%			
Seasonal Field Irrigation Efficiency		67%			
Tomatoes-Fd. 11[h]					
5-18-76	5-18-76	42.00	1.674	S	
6-22-76	6-20-76	83.19	3.317	S&G	
7-22-76	7-15-76	32.04	1.278	G	
8-3-76	NI	6.16	.243	G	
8-7-76	8-5-76	28.96	1.156	S	
8-27-76	8-22-76	22.08	.883	G	
8-31-76	NI	15.30	.609	G	
9-29-76	9-11-76				
Season Total(5/14-10/8)		229.73	9.160		5.782[g]
Percentage Surface Water		35.9%			
Seasonal Field Irrigation Efficiency		63%			
Peppers-Fd. 4 East					
3-13-76	pre-irrigate	27.85	2.374	S	
6-4-76	6-13-76	10.60	.883	S	
6-22-76	6-31-76	17.25	1.461	S	
7-12-76	7-10-76	14.29	1.217	S	
8-5-76[i]	7-31-76	11.79	1.004	S	
8-18-76	8-17-76	13.06	1.126	S	
8-28-76	8-27-76	20.33	1.735	G	
10-5-76	9-20-76	11.71	1.004	G	
Season Total		126.88	10.804		7.803[j]
Percentage Surface Water		75%			
Seasonal Field Irrigation Efficiency		72%			
Tabasco Peppers-Fd. 2					
4-12-76	pre-irrigate	6.16	1.156	S	
4-22-76		3.20	.609	S	
5-12-76		3.82	.730	G	
5-15-76	5-15-76	4.81	.913	S	
6-2-76	6-2-76	8.24	1.557	G	
6-20-76	6-30-76	8.26	1.565	G	
7-8-76	7-16-76	5.55	1.065	G	
8-8-76	8-5-76	5.61	1.065	G	
8-18-76	8-17-76	8.21	1.552	S	
9-2-76	9-1-76	7.15	1.339	S	
9-27-76[k]	9-21-76	7.21	1.369	S(55%)	
10-5-76					
Season Total		68.22	12.920		7.803[k]
Percentage Surface Water		54%			
Seasonal Field Irrigation Efficiency		60%			
Tabasco Peppers-Fd. 7					
5-14-76	5-14-76	9.21	.560	S	
5-18-76		11.21	.680	S	
5-20-76	6-3-76	11.03	.669	G	
6-12-76	6-20-76	16.54	1.004	S	
6-26-76	7-2-76	18.98	1.156	G	
7-15-76	7-13-76	19.72	1.187	S	
8-2-76	8-3-76	12.54	.761	S	
8-20-76	8-18-76	35.37	2.156	G	
9-3-76	9-2-76	18.49	1.136	S	
9-21-76	9-21-76	6.14	.375	S	
10-1-76		13.19	.801	S	
Season Total		172.42	10.485		7.803[k]
Percentage Surface Water		62%			
Seasonal Field Irrigation Efficiency		74%			

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[a] S - Surface Water

[b] G - Groundwater

[c] No irrigation recommended

[d] Received tail water from Field 3

[e] Field #6 irrigated at the same time as Field 5, with the same amount and ET

[f] Gregory, E. J. and Eldon G. Hanson, Predicting Consumptive Use with Climatological Data, New Mexico Water Resource Research Institute, Report No. 066, April 1976

[g] Seasonal estimate based on minimum value measured in San Joaquin Valley, California, Vegatative Water Use, Bulletin 113-3, Department of Water Resources, California

[h] Harvesting started 9-18 and continued through 10-8, with irrigation between first and second picking

[i] Irrigated Cotton Field 4-West at same time

[j] Blaney, Harry F. and Eldon G. Hanson, Consumptive Use and Water Requirements in New Mexico, New Mexico State Engineer, Santa Fe, New Mexico, Technical Report 32, 1965

[k] Other areas irrigated

The last column in Table 2 is the average daily applied water m^3/ha over the total acreage. The applied water represented a low application rate compared to the normal consumtive use of a crop. However, if the daily rate is divided by the ratio of the projected area of the trees to the total area (48%), then the daily rate approaches the daily consumptive rate which is responsible for a small pecan tree (3). The daily irrigation rate will be increased this next year to adjust for the tree growth.

One of the problems associated with the successful operation of a drip-irrigation system is to have an adequate filter system. The original screen filter system installed was inadequate, passing sand particles through it, and was subsequently replaced by a sand filter system. Another problem associated with the drip-irrigation system is the possibility of an accumulation of salts. As can be observed in Table 3, there were more salts in the 5th and 6th foot depths beneath the pecan orchard than beneath the alfalfa and lettuce fields. Because salinity analysis was not done before the initiation of the drip-irrigation system, it is not possible to determine that the salts are the result of the irrigation system. However, salt buildup will be followed carefully in the future. This should be a standard procedure with the initiation of a drip-irrigation system onto a field until experience is acquired about the operation of the system and its affect on salt buildup. As long as the high salt level remains at the bottom of the root system, no damage is expected to the trees. With the high irrigation efficiencies made possible with the drip system, it is expected that the salts will remain captured in the lower depths and not return to the groundwater system through return flow.

The flow rates in the La Mesa Drain are presented in Figure 2 along with the measured salinity and the groundwater level. As may be observed, the flow rates in the drain are cyclic, increasing when irrigation practices start in March and decreasing at the end of the irrigation season in October with a very short lag response time (approximately 15 days). There is a negative correlation between water quality in the drain and flow rates. The flow rate is presented only for the drain at the input to the farm area, because it was impossible to detect, within the degree of measurement accuracy, any increase in the flow as the drain passed through the farm. Consequently, the measured values in the drain are representative of a regional response and not the local response of the farm.

TABLE 2

Irrigation water applied on pecans by trickle irrigation system by weekly irrigation periods, EPA Demonstration Farm, 1976.

*Irrigation Period**	*Applied Water*	*Average Daily Applied Water*	*Total Applied Water*	*Total Average Daily Applied Water*
	(m^3/tree)	(m^3/day/tree)	(m^3/ha)	(m^3/ha)
5-12/5-19	.47	.071	.115	1.66
5-20/5-27	.48	.069	.117	1.47
5-30/6-4	.35	.058	.087	1.44
6-11/6-18	1.46	.209	.361	4.47
6-21/7-1	.28	.028	.069	0.63
7-2/7-10	.13	.053	.105	1.16
7-11/7-17	.43	.061	.105	1.49
7-22/7-29	.20	.030	.059	.74
7-30/8-5	.82	.118	.202	2.88
8-6/8-27	.38	.018	.509	2.30
8-30/9-7	.28	.030	.143	1.77
9-8/9-14	.17	.025	.040	.61
9-22/10-1	1.06	.089	.261	2.17
Total			2.170	

*Divided into weekly irrigation periods; trickle irrigation system operated on continuous basis.

Note: Seasonal rainfall from March 1 to October 31 recorded at the New Mexico State University Plant Science Farm was 22.19 cm.

326 pecan trees on 1.3 ha (Field #1). Pan evaporation 5-12 to 10-1, 1976 equal to 119 cm, applied water/pan evaporation = 0.18.

It is interesting to note that although the flows in the drain increased substantially during the summer months, the groundwater table, as measured by the piezometer located 426 meters from the drain, remained almost constant.

The demonstration project is concerned with presenting the results on the Demonstration Farm to the general public.

The extension personnel have been involved in conveying the information gained from the farm study to interested groups through media releases, tour brochures, and field day presentations.

CONCLUSIONS

Return flow to the river system through deep drainage can be decreased by increasing irrigation efficiencies. One of the side effects

TABLE 3

Soil analyses for salt content for selected samples, EPA Demonstration Farm, January 6, 1977.

Plant Type	Sample	E.C.	pH	Saturation	Concentration*							
					Ca	Mg	Na	K	Cl	CO_3	HCO_3	SO_4
	(cm)	(mmhos)		(%)	(meq/L)							
Alfalfa	0.0- 7.5	.92	7.73	32.5	4.24	1.48	3.84	.51	1.89	0	4.04	4.16
	7.5- 15.0	.89	7.77	29.8	4.13	1.42	3.95	.21	1.70	0	3.50	4.44
	30.0- 37.5	.82	7.85	31.1	3.16	1.24	4.17	.21	1.86	0	3.02	4.36
	60.0- 67.5	1.22	8.03	28.9	3.95	1.41	9.22	.26	2.96	0	3.26	8.00
	90.0- 97.5	2.31	8.03	25.6	3.76	2.92	18.28	.39	6.76	0	3.18	15.40
	120.0-127.5	1.03	8.20	23.8	2.18	.99	8.02	.19	2.42	0	1.48	7.20
	150.0-157.5	.74	8.35	22.0	1.59	.59	6.24	.14	1.98	0	2.08	3.96
	175.0-182.0	.54	8.54	25.8	.68	.38	4.59	.14	1.62	0	1.68	2.52
Lettuce	0.0- 7.5	1.58	8.08	61.3	4.28	2.31	7.87	.58	4.91	0	2.18	7.60
	7.5- 15.0	1.61	7.94	56.2	4.60	2.85	7.74	.65	4.91	0	3.08	7.70
	30.0- 37.5	1.19	8.15	40.4	2.76	1.98	5.97	.45	3.29	0	2.40	5.10
	60.0- 67.5	.88	8.29	31.9	1.81	1.47	4.75	.32	2.13	0	1.54	3.60
	90.0- 97.5	1.02	8.48	30.1	2.24	1.54	5.28	.31	2.48	0	1.54	5.00
	120.0-127.5	.61	8.35	33.8	.53	.75	4.75	.20	1.20	0	1.98	2.76
	150.0-157.5	.74	8.32	28.8	1.91	.72	5.84	.22	2.13	0	1.78	4.70
	175.0-182.0	.97	8.28	24.2	1.22	1.22	7.39	.20	2.15	0	2.46	5.08
Pecan samples located at tree trunk	0.0- 7.5	1.21	7.88	50.0	1.95	1.68	8.30	1.07	3.12	0	5.50	5.00
	7.5- 15.0	1.11	7.85	50.1	2.01	1.64	7.94	.94	2.76	0	5.64	4.70
	30.0- 37.5	1.25	8.01	66.2	1.31	1.26	10.05	.88	4.58	0	2.58	6.10
	60.0- 67.5	1.81	8.01	50.4	4.13	1.46	14.91	.05	6.67	0	3.38	10.60
	90.0- 97.5	4.00	7.83	54.8	21.51	8.20	25.64	.60	5.08	0	.84	51.60
	120.0-127.5	7.58	7.99	50.5	14.43	15.14	54.90	.79	5.62	0	1.46	73.60
	150.0-157.5	5.55	8.26	34.5	7.69	7.39	53.62	.45	19.11	0	1.46	48.80
	175.0-182.0	5.33	8.26	31.3	5.43	5.87	55.54	.47	18.23	0	1.62	44.40
Pecan samples located .5 m from trunk of tree	0.0- 7.5	1.27	8.02	46.1	2.94	1.56	8.86	.91	4.29	0	4.54	5.40
	7.5- 15.0	1.09	8.08	50.8	3.20	1.13	7.58	.75	3.48	0	3.34	5.40
	30.0- 37.5	1.53	8.06	71.7	1.42	1.17	13.45	.36	4.16	0	2.16	9.90
	60.0- 67.5	4.25	7.88	85.0	22.14	9.12	28.83	.50	7.07	0	1.20	51.60
	90.0- 97.5	4.41	7.85	52.3	18.38	9.91	29.68	.45	11.34	0	1.32	48.80
	120.0-127.5	6.40	7.95	46.4	15.38	12.52	54.26	.54	23.16	0	1.32	60.80
	150.0-157.5	5.64	8.36	35.1	6.63	6.93	55.76	.43	20.54	0	1.48	47.60
	175.0-182.0	7.17	8.21	33.0	5.93	7.97	74.04	.50	28.61	0	1.50	60.00
Pecan samples located 1 m from trunk of tree	0.0- 7.5	1.11	8.08	49.0	3.88	1.27	7.70	.72	3.86	0	3.48	5.80
	7.5- 15.0	4.34	7.91	80.1	17.77	9.81	29.68	.43	12.87	0	1.26	46.00
	30.0- 37.5	1.40	8.12	53.7	1.57	1.19	11.15	.63	4.75	0	3.18	7.10
	60.0- 67.5	2.58	7.99	85.0	5.07	3.19	21.37	.51	8.35	0	1.72	20.20
	90.0- 97.5	1.76	8.24	30.5	4.92	1.77	13.78	.24	5.66	0	2.06	13.20
	120.0-127.5	5.33	7.98	35.1	16.50	8.28	40.06	.69	21.52	0	13.6	44.00
	150.0-157.5	6.72	8.21	31.9	11.89	10.40	60.37	.59	26.90	0	1.36	57.20
	175.0-182.0	1.48	8.58	23.1	.53	.86	13.68	.16	3.85	0	2.22	9.30
Pecan samples located 2.7 m from trunk of tree	0.0- 7.5	2.11	8.03	49.4	6.17	2.43	14.57	.87	7.32	0	2.86	14.20
	7.5- 15.0	2.20	8.14	53.6	6.15	2.41	16.01	.86	7.69	0	2.26	15.60
	30.0- 37.5	3.71	8.00	54.5	12.73	5.10	30.06	.83	14.80	0	1.46	37.60
	60.0- 67.5	4.91	7.84	80.9	20.47	10.37	34.44	.72	15.31	0	1.28	48.00
	90.0- 97.5	4.44	7.97	29.8	20.33	9.75	29.12	.45	10.93	0	1.22	46.00
	120.0-127.5	5.06	8.16	36.8	10.82	8.13	43.70	.47	21.38	0	1.18	38.00
	150.0-157.5	3.63	8.32	28.0	4.70	4.32	34.25	.30	11.29	0	1.80	30.80
	175.0-182.0	1.41	8.45	25.5	1.16	1.08	12.68	.18	2.78	0	1.50	10.50

*Based on analysis of saturation extract samples at indicated saturation percent.

from increased irrigation efficiency is a decrease in the amount of fertilizer that is needed to be applied to the fields because less of the applied fertilizer will be leached out of the root zone. In most cases during 1976, the recommendations given to the farmer by the irrigation scheduling service were followed, resulting in a reasonable farm-irrigation efficiency and consequently a minimum return flow rate. However, the farm efficiency can be improved with closer cooperation between the farmers' irrigation dates and the irrigation dates recommended by the irrigation scheduling service. The feasibility of using irrigation scheduling techniques is supported by the response on the Demonstration Farm and by the fact that the scheduling service is commercially available and is being used by other farmers in the valley. The use of a trickle-irrigation system to supply the consumptive use of a pecan orchard resulted in a substantial water saving and consequently a reduced return

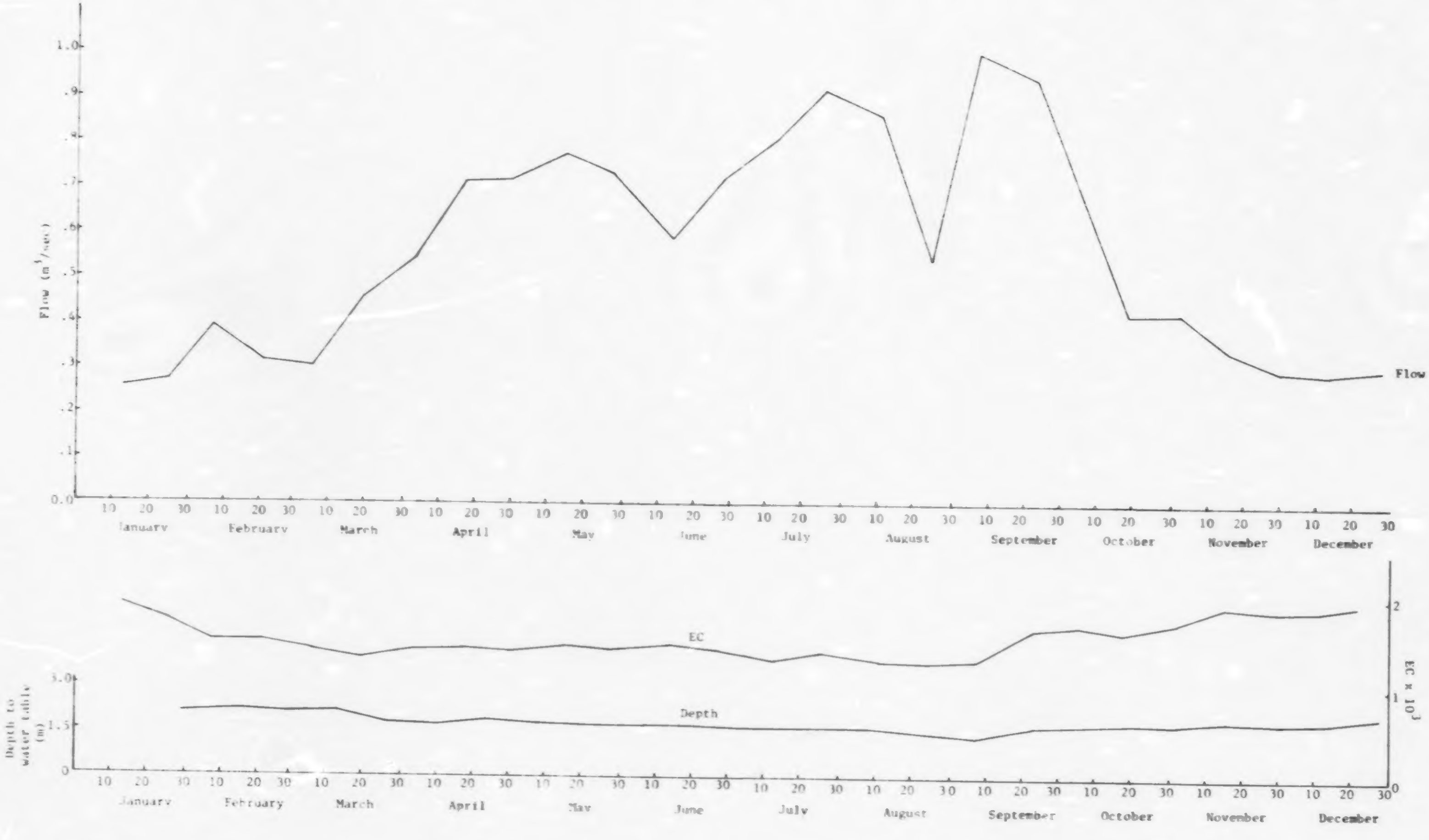

Figure 2. Flow rates and water quality in the La Mesa Drain along with the associated ground-water depth fluctuations.

flow. However, the salts problem associated with the pecan orchard needs further investigation and monitoring.

In the Mesilla Valley, the response time of the drain system to changes in deep drainage is very rapid. Consequently, any farm practices over a large area that affects return flow quantity and quality will immediately be observed in the response of the system.

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ECONOMICS OF CONTROLLING IRRIGATION RETURN FLOW IN THE MESILLA VALLEY, NEW MEXICO

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ABSTRACT

Preliminary budgeting indicates that net returns of water are reduced by incorporation of irrigation water management practices, but that irrigation water requirements may be reduced. Thus, incorporation of these improved irrigation water management practices may be feasible under restricted water availability constraints. If irrigation water use can be reduced without affecting the local agricultural economy by optimal crop selection incorporating the improved practices, the quantity of irrigation return flows may be reduced and possibly the quality may be improved. Further evaluation in the current and last year of the three-year project will provide opportunities for refinements and sensitivity evaluation in the linear programming model as well as more extensive iterative analysis with the hydrological model.

INTRODUCTION

The quality of irrigation return flow represents a major problem in the western United States because of the goal of restoring and maintaining the quality of the nation's waters as required by the Federal Water Pollution Control Act (PL 92-500). The water of the Upper Rio Grande has been reported as a classic example of water quality degradation.

A U.S. Senate Select Committee (1961) report estimated that the Upper Rio Grande and Pecos Basins were the shortest of water in relation to projected demand to 1980 of any basin in the continental United States. This projection was documented by the U.S. Water Resources Council study (1968) which studied the complete Rio Grande drainage area in Colorado, New Mexico, and Texas. The Water Resources Council study identified the major problems to be water deficiencies and groundwater storage depletion, poor quality because of mineral pollution, heavy sediment loads in many tributaries, excessive non-beneficial consumptive use, and frequent floods causing extensive damage.

The Council further stated that these water problems must be solved since projected water withdrawals for the year 2020 are estimated to be about two and one-half times greater than the present average runoff in the region.

The Upper Rio Grande from the headwaters in Colorado to Fort Quitman, Texas (Figure 1) probably comes closer to consumptively using all of the surface water of the river than any other major river basin in the United States. The only surface waters that escape the region at Fort Quitman are occasional flood waters from thunderstorms. Therefore, concentration of dissolved solids became a major problem in the southern reach of the basin. Table 1 indicates the variation in composition of the Rio Grande water from Otowi Bridge near Santa Fe to El Paso, Texas. It shows a progressive increase in the concentration of total dissolved solids and percent sodium from the upper to the lower sampling stations. The relatively large increase in dissolved solids in the river along

TABLE 1

Surface water quality of the Rio Grande at selected gaging stations, 1967

Station	Average Discharge CFS	Ca mg/e	Ma mg/e	Na mg/e	Cl mg/e	SO4 mg/e	HCO3 mg/e	Dissolved Solids mg/e	Electrical Conductivity Ec x 10^6 at 25°C
Rio Grande at Otowi Bridge 1967 Water Yr.	802	49	8.0	29	8.6	81	150	276	429
Rio Grande Conveyance Channel at San Marcial 1967 Water Year	454	90	16	99	—	—	218	632	972
Rio Grande at El Paso, Texas 1967 Calendar Year	321	87	19	151	130	262	—	809	1,220

Note: Discharge and quality parameters are time averaged. Parameters not measured or reported are identified by —.

the irrigated areas is mainly due to the concentrating effect of irrigation water withdrawals and/or return flows. Plants take up water from the soil solution and transpire it to the atmosphere, but they take up very little salt.

Because of the concern for water quality degradation due to concentration in the Upper Rio Grande Basin, the EPA funded a demonstration project to show the feasibility of alternative water management practices on the quality of drainage return flow and soil salinity in the Upper Rio Grande Basin.

This project consists of three phases: (1) a 450-acre farm demonstration site, (2) a four-acre test site, and (3) evaluation of a hydrosalinity model. On the 450-acre demonstration site, a combination of present-day irrigation techniques is being used to show how, through modern water management, the irrigation return-flow quality and quantity can be improved. The feasibility of irrigating at or near 100 percent efficiency with water of medium salinity (1200 ppm), while maintaining optimum crop yields over a period of many years is being evaluated on a four-acre test site. The hydrosalinity model is being tested for Mesilla Valley conditions in southern New Mexico and extreme west Texas (Figure 1). A paper by Sammis and Hohn reported on the demonstration farm portion of this project. In a previous section of this conference (Water Management), Wierenga and Sisson reported on the four-acre test site.

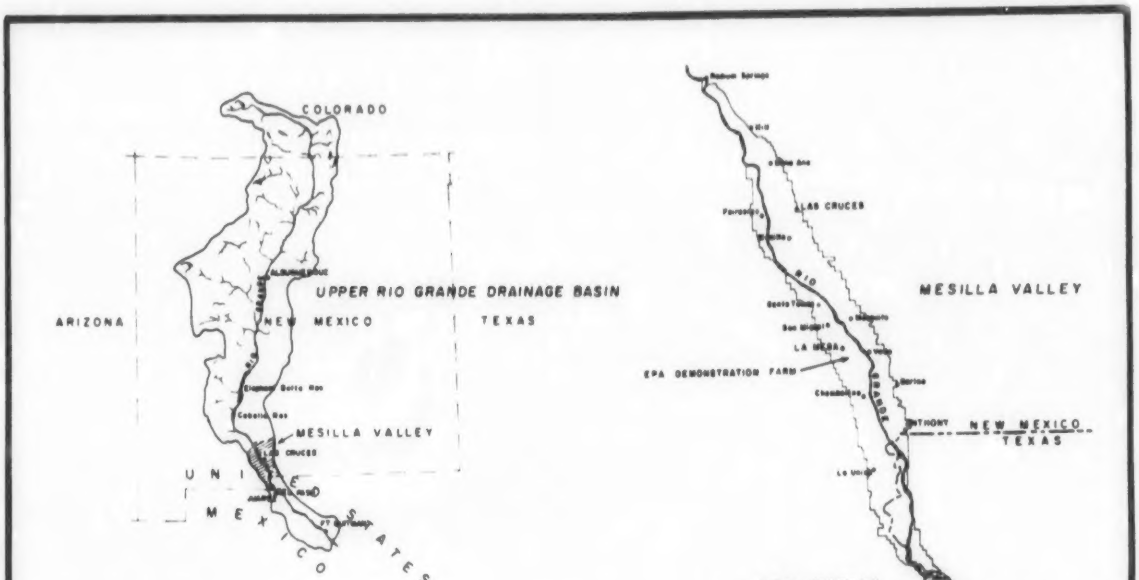

Figure 1. Location of irrigation return flow salinity control demonstration farm in the Mesilla Valley and Upper Rio Grande drainage basin, New Mexico.

The objective of this paper is to project the changes in the quantity of irrigation return flows as a result of alternative water management practices that could be adopted by farmers in the Mesilla Valley. They are (1) irrigation and management scheduling, (2) trickle irrigation on tree crops, and (3) sprinkle irrigation on vegetable crop emergence. The effects of these practices will be simulated for the approximately 100,000-acre Mesilla Valley.

THE ANALYTICAL SYSTEM

The analytical system consists of two specific models sequentially linked to simulate the agricultural production and hydrological adjustments that would occur as a result of implementation of the alternative water management practices. The first is a linear programming model to estimate the economic impact and the irrigation water requirements. The solution is constrained by the usual physical, institutional, and market restrictions. The results of the LP model serve as inputs to the physical model. The physical model is partitioned into interdependent submodels that analyze the hydrology and salinity balances. The submodels estimate the effects of irrigation water use on the water table depths and the quality and quantity of irrigation return flows. Solutions from the models are iterated a sufficient number of times to simulate the hydrologic adjustments from a change in water-use as a result of alternative water management practices.

The Physical Model

The hydrosalinity model selected for this study was developed by the U.S. Bureau of Reclamation (1975) for the Environmental Protection Agency. This discussion of the hydrosalinity model is a summary of material presented at the International Conference on Managing Saline Water for Irrigation in Lubbock, Texas (McLin and Gelhar, 1976). This model can represent a general water and mass balance for a river basin, or portion thereof. The model includes components which simulate surface and groundwater reservoirs, diversions to meet irrigation needs and other uses, irrigation return flows, and chemical transformations in the soil. Several nodes can be used to simulate the conditions in different segments of a basin. The model would be classified as a multicell lumped parameter model. Input data on water use, surface and groundwater quality, and streamflows and diversions are required to operate the model.

The USBR model represents an irrigated area by a series of nodes. The number of nodes depends on the physical features of the study area, the availability of data, and the number of points at which the model response is desired within the area. The model structure is based on water balance for a given time interval which is computed and maintained for each node. The transfer of water between river and aquifer may be essential to maintain this balance. A soil column is included to simulate the chemical exchange between soil and water as water percolates downward through the soil column. The model allows the mixing of one water with another and computes the chemical quality of the mixed waters in proportion to the volumes mixed. Thus, a chemical mass balance is simultaneously maintained. All these computations are performed for one node at a time and progress from the upstream to the downstream nodes.

A node includes simulation of several features as shown in Figure 2. These are: simulation of magnitude and quality of river flow, diversion to meet the irrigation demand, water transfer between river and aquifer, irrigation return flows directly to the aquifer, through the soil to the aquifer, and to the river. The river flow at the start of nodal operation is a known quantity, a portion of which is diverted to meet the irrigation demand. The irrigation return flow is then computed by subtracting the crop consumptive use from the irrigation demand. The chemical quality of mixed waters is computed at each point. At the end of nodal operation, the balance of inflow to, and outflow from, the river is determined. If the river flow is in excess of that observed, the additional water is transferred to the aquifer; if the river flow is in deficit, water is withdrawn from the aquifer to maintain the balance. In the model operation, no consideration is given to spatial variability of hydrologic variables within a node. Hydraulic properties of soil and aquifer are not considered.

The input data needed to operate the model include irrigation demand, crop consumptive use, diversion, river water quality, initial aquifer water storage and chemical quality, soil moisture content and its chemical quality, and precipitation.

Originally, the computer program for the model was written for a Control Data Corporation computing system. To make the program compatible with an IBM 360-44 system, numerous changes involving definition of variables, and format and dimension statements were required. The revised computer program is listed in a recent report (Lansford, et al., 1976) with all of the program changes identified.

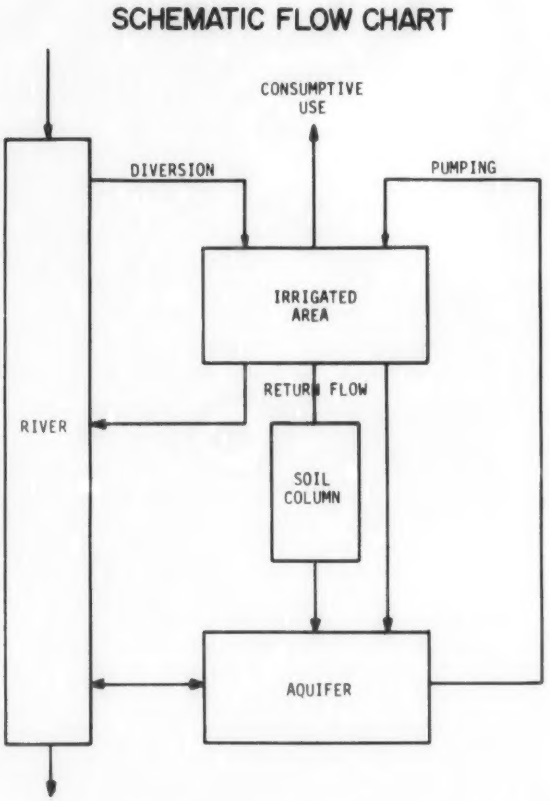
SCHEMATIC FLOW CHART
CONSUMPTIVE USE
DIVERSION
PUMPING
IRRIGATED AREA
RETURN FLOW
RIVER
SOIL COLUMN
AQUIFER

Figure 2. Schematic flow chart showing the features simulated in each node of the model.

Simulation for the Mesilla Valley

The objectives of these simulations are to determine what model structure is suitable for the Mesilla Valley and to test the sensitivity of the model results to observed and estimated input data. The model was implemented with existing field data for the period June 1967 to June 1968. A complete set of groundwater quality data was available at the beginning of this period.

The irrigated areas served by the Leasburg and Mesilla diversion dams form natural nodes for the model (Figure 3). The quantity and chemical quality of flow in these diversions are observed. Each node includes several operational features as shown in Figure 4.

Economic Model

The linear programming model derives a cropping pattern that maximizes returns to water in each of the nodes, subject to the amount of surface and groundwater available and the crop rotation and marketing requirements of the area. The locations of crops were specified in the base year, with the location of additional

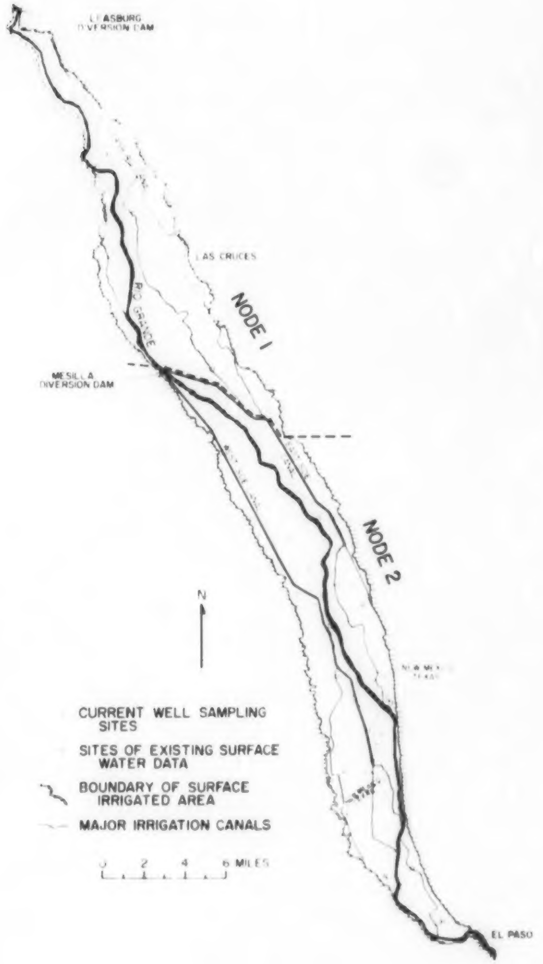
LEASBURG DIVERSION DAM
LAS CRUCES
RIO GRANDE
NODE 1
MESILLA DIVERSION DAM
NODE 2
N
NEW MEXICO
TEXAS
EL PASO
CURRENT WELL SAMPLING SITES
SITES OF EXISTING SURFACE WATER DATA
BOUNDARY OF SURFACE IRRIGATED AREA
MAJOR IRRIGATION CANALS
0 2 4 6 MILES

Figure 3. Location of existing surface data and sampling points. Node 1 contains approximately 40,800 acres; node 2, approximately 67,800 acres.

acreages of crops only being constrained by market characteristics. Water use in the base year approximated actual water use reported by the area irrigation districts. Average commodity prices for 1967-76 are justified by constraining the LP crop production.

Alternative crop production activities and coefficients will be developed by utilizing a submodel budget generator to derive engineering cost approach crop enterprise budgets. The base year budgets will be designed to simulate the cost and returns and input requirements for typical farming operations in the Mesilla Valley. Alternative crop production budgets incorporating irrigation water management practices will be developed by modification of the base year budgets, thus providing a series of levels of irrigation water management practices in the Mesilla Valley.

RESULTS

Experience with the USBR-EPA simulation model has demonstrated the difficulty of routine application of large and complex computer-programs even when the model is designed to be general and flexible. This model is actually computer- and site-specific; several subroutines must be modified for each application and thus requires substantial knowledge of the logic of the entire program.

The preliminary simulation results for the Mesilla Valley indicate a need to improve the input data and model structure (McLin and Gelhar, 1976). Several sensitivity analyses conducted with the model in its preliminary form showed the effects of consumptive water use, soil chemistry, and groundwater chemistry. The scheme originally used in the model to transfer water between the aquifer and the stream may be physically unrealistic in that it is independent of aquifer properties and water level. Improvements which relate the stream-aquifer interaction to aquifer properties and water level (Gelhar and Wilson, 1974) will be incorporated after the model has been tested over a long time frame in its original form. Baseflow recession and well drawdown data will be used to estimate the required aquifer parameters for the proposed model improvements.

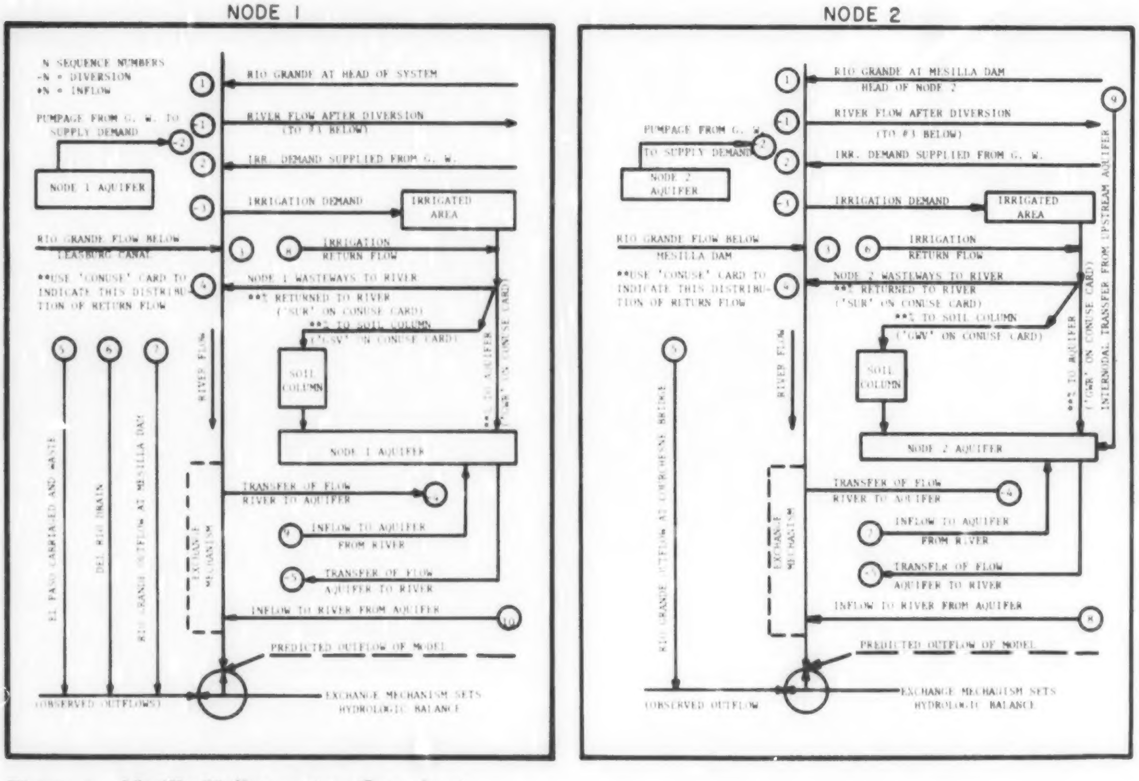
NODE 1
N SEQUENCE NUMBERS
-N = DIVERSION
+N = INFLOW
RIO GRANDE AT HEAD OF SYSTEM
PUMPAGE FROM G. W. TO SUPPLY DEMAND
RIVER FLOW AFTER DIVERSION (TO #3 BELOW)
IRR. DEMAND SUPPLIED FROM G. W.
NODE 1 AQUIFER
IRRIGATION DEMAND
IRRIGATED AREA
RIO GRANDE FLOW BELOW LEASBURG CANAL
IRRIGATION RETURN FLOW
**USE 'CONUSE' CARD TO INDICATE THIS DISTRIBUTION OF RETURN FLOW
NODE 1 WASTEWAYS TO RIVER
**% RETURNED TO RIVER ('SUR' ON CONUSE CARD)
**% TO SOIL COLUMN ('GSV' ON CONUSE CARD)
**% TO AQUIFER ('GWR' ON CONUSE CARD)
RIVER FLOW
SOIL COLUMN
NODE 1 AQUIFER
EL PASO CARRIAGED AND WASTE
DEL RIO DRAIN
RIO GRANDE OUTFLOW AT MESILLA DAM
EXCHANGE MECHANISM
TRANSFER OF FLOW RIVER TO AQUIFER
INFLOW TO AQUIFER FROM RIVER
TRANSFER OF FLOW AQUIFER TO RIVER
INFLOW TO RIVER FROM AQUIFER
PREDICTED OUTFLOW OF MODEL
(OBSERVED OUTFLOWS)
EXCHANGE MECHANISM SETS HYDROLOGIC BALANCE
NODE 2
RIO GRANDE AT MESILLA DAM HEAD OF NODE 2
RIVER FLOW AFTER DIVERSION (TO #3 BELOW)
PUMPAGE FROM G. W. TO SUPPLY DEMAND
IRR. DEMAND SUPPLIED FROM G. W.
NODE 2 AQUIFER
IRRIGATION DEMAND
IRRIGATED AREA
RIO GRANDE FLOW BELOW MESILLA DAM
IRRIGATION RETURN FLOW
**USE 'CONUSE' CARD TO INDICATE THIS DISTRIBUTION OF RETURN FLOW
NODE 2 WASTEWAYS TO RIVER
**% RETURNED TO RIVER ('SUR' ON CONUSE CARD)
**% TO SOIL COLUMN ('GWV' ON CONUSE CARD)
**% TO AQUIFER ('GWR' ON CONUSE CARD)
INTERNODAL TRANSFER FROM UPSTREAM AQUIFER
RIVER FLOW
SOIL COLUMN
NODE 2 AQUIFER
RIO GRANDE OUTFLOW AT CORCHESNE BRIDGE
EXCHANGE MECHANISM
TRANSFER OF FLOW RIVER TO AQUIFER
INFLOW TO AQUIFER FROM RIVER
TRANSFER OF FLOW AQUIFER TO RIVER
INFLOW TO RIVER FROM AQUIFER
PREDICTED OUTFLOW OF MODEL
OBSERVED OUTFLOW
EXCHANGE MECHANISM SETS HYDROLOGIC BALANCE

Figure 4. Mesilla Valley system flow chart

Of the features examined in the sensitivity analyses for the one-year simulation period, it is evident that the average initial chemistry of aquifer waters and the combined effects of crop consumptive use and irrigation efficiency play an important role in the predicted TDS output.

Preliminary budgeting indicates that net returns to water are reduced by incorporation of irrigation water management practices, but that irrigation water requirements may be reduced. Thus, incorporation of these improved irrigation water management practices may be feasible under restricted water availability constraints. If irrigation water use can be reduced without affecting the local agricultural economy by optimal crop selection incorporating the improved practices, the quantity of irrigation return flows may be reduced and possibly the quality may be improved. Further evaluation in the current and last year of the three-year project will provide opportunities for refinements and sensitivity evaluation in the linear programming model as well as more extensive iterative analysis with the hydrological model.

Additional results are expected and will be reported during the conference.

ACKNOWLEDGMENT

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Agricultural Drainage Problems of the San Joaquin Valley

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ABSTRACT

A brief description of the physical setting of the San Joaquin Valley and the drainage problems anticipated are presented. Estimates are preliminary and subject to revision as studies continue.

INTRODUCTION

This paper, in combination with the three which follow it, describes the present and impending agricultural drainage problems in the San Joaquin Valley of California and the efforts of three agencies to cope jointly and comprehensively with these problems. The three agencies are the U.S. Bureau of Reclamation, the California Department of Water Resources, and the California State Water Resources Control Board. They have undertaken what has been named the San Joaquin Valley Interagency Drainage Program — or the IDP, for short.

One purpose of the IDP is to coordinate studies of agricultural drainage water and salt management which the three agencies engage in independently. This coordination should insure that the funds which the three agencies have for studying drainage problems will be spread efficiently over a broad range of work without duplication of effort or omission of essential components. A second purpose is to develop cooperatively an economically feasible, environmentally sound, and politically acceptable plan for managing the agricultural drainage problems of the San Joaquin Valley and for disposing of the salts which are, after all, the fundamental problem.

This paper presents a brief overview of the problem. The three papers which follow will give more details about the problem, the local partial solutions, and some of the possible comprehensive solutions under consideration.

The Physical Setting

The San Joaquin Valley is the southern half of the great Central Valley of California (see Figure 1). The San Joaquin Valley is bounded on the east by the Sierra Nevada Mountains, on the south by the Tehachapi Mountains, on the east by the Coast Range Mountains, and on the north by the Delta formed by the Sacramento and San Joaquin Rivers. The floor of the valley is approximately 200 miles long and about 40 miles wide on the average. The floor slopes upward from sea level at the Sacramento-San

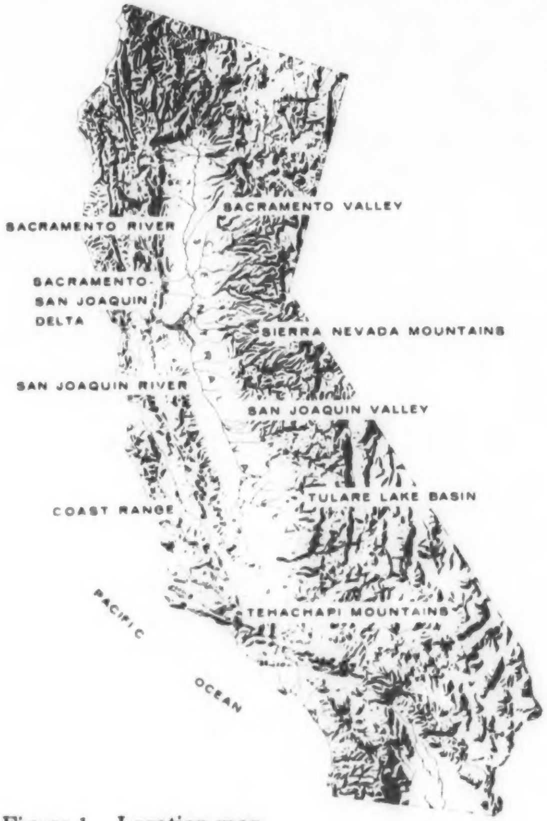

Figure 1. Location map

Joaquin Delta to a rim elevation of from 500 to 700 feet above sea level on the three mountainous sides. An imperceptible drainage divide crosses the San Joaquin Valley from east to west near its midpoint. North of this divide the surface waters drain to the Pacific Ocean via the San Joaquin River, the Sacramento-San Joaquin Delta, and San Francisco Bay. The southern half, known as Tulare Lake Basin, is an interior drainage; only in years of heavier runoff does surface water escape northward to the San Joaquin River and thence to the ocean.

For purposes of this discussion of drainage problems, it is convenient to talk of the San Joaquin Valley in six components rather than to treat the valley as a whole.

One component is the eastern side of the San Joaquin Valley north and east of the San Joaquin River. This is called Eastside North (see Figure 2). Here the soils are moderately or highly permeable. Nearly all of this area has been developed for irrigation using the high quality water which comes from the snowpack of the Sierra Nevada. The combination of permeable soils and high quality water makes it unlikely that this area will ever have drainage problems. Should high water tables develop, most of the water could be reused.

The second area has been named the Eastside South. It lies south of the San Joaquin River bounded on the east by the Sierra Nevada foothills, on the south by the northern boundary of Kern County, and on the west by the Tulare Lake area. As with the Eastside North, most of the Eastside South soils are permeable or moderately permeable and it has a supply of high quality irrigation water from the Sierra Nevada runoff. It does not have enough of this high quality water, however, to irrigate all of the irrigable land. Consequently, at some future time, water will have to be imported to overcome the ground water overdraft that now exists in the area. The imported water may contain moderate amounts (300-800 milligrams/liter) of salt and ultimately will cause a drainage problem. The problem most likely will manifest itself on the west side of the component area near the valley trough.

The third component area is the service area of the Delta-Mendota Canal. It lies west of the San Joaquin River and extends from almost the Sacramento-San Joaquin Delta to the San Luis service area. These soils are appreciably tighter than those of the east side and a large portion of the water supply is imported with a salinity of 300-800 mg/l. The remainder of the water supply is either ground water or local west side runoff, both of which are as saline, or perhaps more saline, than the imported supply. Irrigation development in this area began more than 100 years ago using water from the San Joaquin River. With the completion of the Delta-Mendota Canal 25 years ago, the San Joaquin River water was replaced by the imported water and the area of irrigation was expanded. A few localized drainage problems have developed.

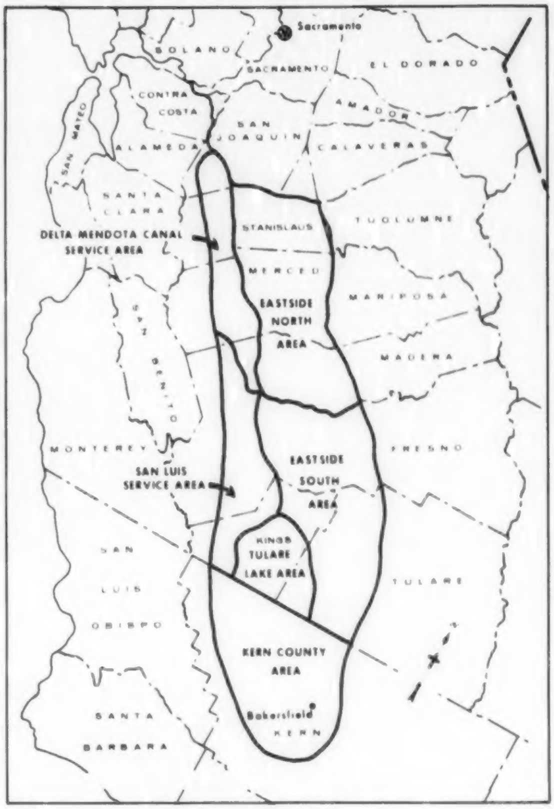

Figure 2. Designated drainage areas in San Joaquin Valley

South of the Delta-Mendota Canal service area lies the San Luis service area. Here again the soils are tighter than those on the east side, in some cases being only slowly permeable. The area is interspersed with impervious strata which result in numerous perched water tables. The drainage picture is further complicated by the fact that the water supply is either imported water or water pumped from the underground. In both cases there is an appreciable saline content. Drainage problems have been slowly increasing in this area with the growth of irrigation. Even before irrigation development, however, natural conditions produced pockets of highly saline shallow ground water along the trough line of the valley. In some cases, these perched water bodies have salinities of 100,000 mg/l.

The fifth component area is the Tulare Lake area. It is the bed of what under natural conditions in recent geologic times was an intermittent shallow lake or marsh. The instigation of upstream irrigation developments, which reduced the inflow, and the construction of a series of diked ponds in which to manage the runoff which did reach the old lake, have permitted the reclamation and agricultural development of the area. The salts which have accumulated in the soils over the centuries and the tightness of the lacustrine soils have combined to produce one of the most serious and immediate drainage problems in the San Joaquin Valley.

The sixth component area is the Kern County portion of the valley floor. In many respects it is similar to the Tulare Lake area. Unlike the Tulare Lake area, however, the Kern County area had only a severely limited water supply until the late 1960's. Now it receives supplemental imported water from two sources. It can be anticipated that drainage problems will develop rapidly in the Kern County area.

The Ultimate Magnitude of the Drainage Problem

The San Joaquin Valley Interagency Drainage Program has estimated the annual quantities which may be captured in a master drainage facility. This of course, will not be all the bad quality water that will result from the irrigation and the concentration of salts by the plants in the soil. Some of the bad quality water will escape past tile drains into the ground water and will show up elsewhere. How much is captured for management and disposal depends upon the efficiency of water application by the irrigator and the efficiency of the tile drainage system.

On the Delta-Mendota service area, we anticipate that ultimately about a million and a half acre-feet of water will be applied annually for irrigation. We assumed a basin efficiency of 87 percent, and this means that 196,000 acre-feet of waste water will be generated every year. If we can capture 50 percent of this, we will have about 100,000 acre-feet of recoverable waste to our drain from the Delta-Mendota service area.

In the San Luis service area, we anticipate an ultimate annual application of about 1,760,000 acre-feet. The efficiency of use within the area will range from 86 percent to 94 percent and about 216,000 acre-feet of poor quality water will be generated each year. We anticipate recovering approximately 70 percent of this, or 150,000 acre-feet annually.

In the Eastside South area, ultimately about 4,900,000 acre-feet of water will be applied at efficiencies ranging from 85 percent to 94 percent. This will produce 380,000 acre-feet of waste water to be disposed of, and we expect that from 50 percent to 70 percent of it will be recovered in a master drainage facility, or about 220,000 acre-feet.

In the Kern County area, ultimately 2,980,000 acre-feet of water will be applied with efficiencies ranging from 92 percent to 96 percent. Thus, 205,000 acre-feet of waste water will be produced untimately each year and we will be able to capture somewhere between 65 percent and 75 percent of it for a total of 140,000 acre-feet of poor quality water discharged to the drain each year.

For the Eastside North area, we anticipate that 860,000 acre-feet a year will be applied with an efficiency of 85 percent. This means 129,000 acre-feet of drainage water will be generated, but only about 20 percent or 25 percent of it, or about 30,000 acre-feet, will be of such poor quality as to require disposal via a master drain.

We expect the Tulare Lake area to generate ultimately about 200,000 acre-feet of poor quality drainage water per year. Three-fourths of this will be disposed of in local drainage ponds, but the remaining 50,000 acre-feet probably will have to be disposed of via a master drainage facility. These estimates are based on observations of existing practice in the area rather than by estimating application and drainage efficiencies. The volume of water applied varies so much from year to year in this area (due to lack of upstream regulatory storage) that any implication of a fairly constant irrigation efficiency would be misleading.

The Buildup of the Drainage Quantities

Estimating the rate at which drainage flows will build-up in a master drain for an area such as the San Joaquin Valley undoubtedly is much more of an art than a science. The first question to be answered is when will the water supply development be complete. At the present time the Eastside North area, the Delta-Mendota service area, and the Tulare Lake Basin area have adequate supplies. The San Luis service area is in the process of building up its annual use of supplemental water as is the Kern County area. The Eastside South area, however, is seriously deficient in water supply and there still is great uncertainty about what sort of water development project will be built to supply this area.

After the question of the rate of buildup of water supply comes a question of the action of the shallow ground water table. For the San Joaquin Valley Interagency Drainage Program, we have assumed that areas which develop a shallow ground water table within 5 feet or less of the surface will have to have drainage provided. There are some areas in the San Joaquin Valley, however, that have been operating for years with full irrigation and a shallow ground water table within 5 feet of the surface. The shallow ground water shows no sign of rising, and no drainage is required. Consequently, we must recognize the fact that very low rates of permeability which are difficult to measure accurately may nevertheless be adequate to carry away the leaching water from an efficient farm operation.

Finally, of course, in order to know how the drainage quantities will build up with time we must predict how the individual farmers will install the tile drains. This is a matter of individual economic judgment on the part of each farmer and one which is very difficult to foresee. The timing will be further complicated by the related factors of financial assistance which may be made available to farmers for installing tile drains, and the availability of the drains themselves, and the people to install them. Experience has shown that in the Coachella Valley in southern California at least, the latter factor may be the limiting one as far as the rate of installation of the tile drain systems is concerned. At any rate, we have done our best in these three areas of uncertainty and have come up with estimated rates of growth of the drainage qualities, decade by decade, through the year 2080 (see Table 1).

TABLE 1

Estimated annual quantities of subsurface agricultural drainage water in the San Joaquin Valley.

	1980		2000		2020		2040		2060		2080	
Subarea	1000 *A.F.*	1000 *Acres*	1000 *A.F.*	1000 *Acres*	1000 *A.F.*	1000 *Acres*	1000 *A.F.*	1000 *Acres*	1000 *A.F.*	1000 *Acres*	1000 *A.F.*	1000 *Acres*
Delta-Mendota Canal service area	35	40	50	60	60	75	80	100	100	125	100	125
San Luis service area	10	20	70	140	110	220	120	240	130	260	150	300
Tulare Lake[1]	5	8[1]	20	27	30	40	40	60	50	75	50	75
Tulare Lake[2]	(20)	(30)[2]	(60)	(80)	(100)	(150)	(135)	(200)	(150)	(215)	(150)	(215)
Eastside South	0	0	50	125	120	300	180	450	200	500	220	560
Kern County	0	0	40	55	80	115	120	175	130	190	140	205
Eastside North[1]	0	0[1]	5	6	10	12	20	24	30	35	30	35
Eastside North[3]	(100)	(120)[3]	(100)	(120)	(100)	(120)	(100)	(120)	(100)	(120)	(100)	(120)
Total	50	68	235	413	410	762	560	1,049	640	1,185	690	1,300

[1] Export via a valleywide drain system.

[2] Retained drainage water to be disposed of in local evaporation ponds — not included in totals for valleywide system.

[3] Leaves subarea via San Joaquin River, ground-water flow to west side, evaporation and consumptive use on nontilled areas.

Quality of the Drainage Effluent

The quality of the drainage effluent is an all-important factor in deciding what kind of disposal management will be required. The estimates of amounts of water applied, the quality of the applied water, and the efficiency of application lead us directly to the quality of the effluent. There is, however, one somewhat empirical factor to be taken into account. This is the existence of the pockets of the highly saline perched ground water along the trough of the San Joaquin Valley. Because of the presence of these perched water tables, the estimated overall quality of the drainage effluent begins at a poorer quality and decreases as time progresses, finally leveling off.

The valley-wide average quality of the agricultural drainage to be disposed of from the San Joaquin Valley through a master drainage facility is expected to vary as follows:

	Quality	
Year	*Electrical Conductivity*	*Total Dissolved Solids*
	micromhos/cm	mg/l
1980	7,500	5,200
2000	5,500	3,800
2020	5,000	3,500
2040	5,000	3,500
2060	4,500	3,200
2080	4,300	3,000

CONCLUSION

This completes a brief description of the physical setting of the San Joaquin Valley and of the drainage problems which we anticipate there. Needless to say, these estimates I have given you are preliminary and subject to revision as our studies continue.

How the NPDES Program Will Define Present Water Quality Conditions

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ABSTRACT

Monitoring of surface irrigation supplies and surface return flows is being carried on through the NPDES permit program under Public Law 92-500. This program encompasses approximately 1.3 million acres of land in the San Joaquin Valley of California alone. The EC and suspended solids of the irrigation returns frequently exceed basin water quality control plan objectives (standards) adopted in 1971 by the Central Valley Board for the receiving water.

The NPDES irrigation return flow monitoring program is administered in California through the State Water Resources Control Board and nine regional water quality control boards. The largest regional board is the Central Valley Regional Water Quality Control Board which covers 6.8 million of the State's 8.8 million acres of irrigated land. The San Joaquin Valley lies in the southern portion of the Central Valley region and contains approximately 4,500,000 acres of irrigated land.

Water quality standards, called objectives, have been set for some surface streams by the Central Valley Board. An example is the objective of 500 ppm salinity (total dissolved solids) at Vernalis on the San Joaquin River. Any discharge to the river, including agricultural returns, can be restricted by the Regional Board to meet these objectives and keep river salinity below 500 ppm. This course of action has not been pursued, lacking concomitant alternative actions such as development of a dilution water supply and a saline water drainage facility. Another water quality objective for the San Joaquin River allows discharges to increase turbidity a small amount over background levels — usually a 10 percent increase. Enforcement of turbidity objectives has been delayed for most agricultural discharges pending development of sufficient data and selection of appropriate available technology.

When faced in 1974 with the issue of administering a permit program for irrigation returns, California sought advice from a State Agricultural Water Quality Advisory Committee. The committee, composed of irrigation and water leaders and technical persons, recommended:

1. Regional Boards issue permits to water purveying and draining entities, be they districts or individual farms.
2. Allow grouping of entities into single permits around hydrographic areas to facilitate sampling and permit issuance.
3. Initially the permittees to monitor three items — quantity of flow, both supply and discharge; salinity (electrical conductivity); and suspended solids (primarily sediments).

At this time 22 NPDES permits covering 2.9 million acres of irrigated lands have been issued in the Central Valley Region (Sacramento and San Joaquin Valley). Monitoring has been carried on for up to two years by some permittees. Table 1 shows permits issued in the San Joaquin Valley area. These do not include 3,100,000 acres of land in the south half of the San Joaquin Valley (Tulare Lake Basin), as in this more arid location return flows to surface streams are very infrequent. A monitoring program is being devised for this area and will be carried out under section 208 of PL 92-500 rather than the permit section.

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San Joaquin River irrigation return flows constitute, in normal water years, a significant portion of the irrigation season flow of the San Joaquin River. In the permit areas, surface irrigation returns and subsurface irrigation returns are usually co-mingled. Thus, the monitoring sites, which are mostly located near discharges to the river, represent a combination of surface and subsurface runoff or drainage.

Table 2 shows preliminary estimates and measurements of quantities of water supplied through canal conveyances for four permittees. Supply locations were selected by sites that represented at least 80 percent of the total surface water supply to a permit area. Groundwater sources are not reported although some existing data is available. If it is assumed that typical applied irrigation water is 3-1/2 acre feet per irrigated acre in the permit areas indicated, then the percentage of the supplies monitored would be as indicated in the table.

The table also shows preliminary estimates and measurements of quantities of return flows. The percentage of total returns which these are thought to represent are indicated in the table. Representative supply and surface return flow sites described above were selected with assistance from irrigation district staff, consultants, representatives of the Soil Conservation Service, Agricultural Extension Service and others.

The Central Valley Board looks at the salinity issue as a problem requiring a basin-wide solution; i.e., the Board looks to the Inter-Agency Drainage Program, the Basin Plan and other sources for solutions. Typical electrical conductivities (EC) of supply and discharge water are shown and compared in Table 3. It can be seen that a relatively high discharge EC of "westside" permit areas indicates a need for drainage facilities to separate and remove saline drainage waters from the return flows. The higher EC of "westside" permit areas is considered to be largely due to relatively higher EC of supply waters in that area.

Table 3 also shows typical suspended solids concentrations in supply and discharge waters. Field observations indicate that high sediment loads in the discharges are mainly due to irrigation conditions. More detailed studies made by the University of California, the Soil Conservation Service, and the Stanislaus County Public Works Department confirm that the sediment loads are from irrigation surface returns. These organizations are working with the local Resource Conservation District, the Central Valley Board staff and others to identify and implement solutions to the sediment problem.

During the process of selecting monitoring points, persons with local irrigation and agricultural expertise were invited to informal discussions and were asked to make suggestions. These discussions were useful in that monitoring and research activities by other organizations and agencies were found to complement the NPDES monitoring program. Initially it was thought that more internal monitoring would be included in the NPDES permits. However, as a result of these informal discussions, some of the research and investigations of others were directed to meet much of the initial internal monitoring needs.

In addition to the parameters of flow, salinity, and suspended solids, the Central Valley Board is cooperating with other organizations such as the California Department of Fish and Game to look into possible problems of agricultural chemicals in irrigation flows.

The NPDES permit program has not been accepted without reservations by a wary agricultural community. There has been, however, some recognition in the value of participating in the program and some monitoring findings have been made which were not anticipated. For example, it was found that there is a substantial daily variation in the EC of the water supplied through the USBR Delta-Mendota Canal to the Mendota-Crows Landing area.

SUMMARY

Monitoring of surface irrigation supplies and surface return flows is being carried on through the NPDES permit program under Public Law 92-500. This program, administered by the State of California, encompasses approximately 1.3 million acres of land in the San Joaquin Valley of California alone. Sampling locations are usually located near the point of discharge to surface waters. The EC and suspended solids of the irrigation returns frequently exceeds basin water quality control plan objectives (standards) adopted in 1971 by the Central Valley Board for the receiving water, in this case the San Joaquin River. The solution to the high EC problem lies in basin-wide management of saline waters including large scale drainage conveyances where appropriate. The solution to the high suspended solids is being sought through investigations being conducted by local Resource Conservation Districts, Soil Conservation Service, and Agricultural Extension Service personnel.

TABLE 1

NPDES Irrigation Return Flow Monitoring in the San Joaquin Valley

Permittees	Irrigated Acres	Date Permit Issued	Date Monitoring Began	Monitoring Number Supply Points	 Number Discharge Points
Central Delta Water Agency	120,000	8/27/76	—	—	—
South Delta Water Agency	102,000	8/27/76	—	—	—
Patterson Resource Conservation Dist.	50,000	5/28/76	6/76	3	3
Mendota-Crows Landing Return Flow Group	400,000	7/25/75	8/75	2	3
Stanislaus-Tuolumne Rivers Water Quality Committee	200,000	8/22/75	9/75	2	8
Byron-Bethany Irrigation Dist.	11,000	8/27/76	9/76	1	3
Turlock Irrigation Dist.	170,000	8/22/75	9/75	1	2
Merced Irrigation Dist.	110,000	8/22/75	9/75	1	3
Madera County Flood & Water Conservation Dist.	150,000	3/26/76	7/76	3	6
Columbia Canal & Newhall Land & Farming Co.	21,000	8/22/75	8/75	—	2
El Nido Irrigation Dist.	9,000	8/27/76	—	1	—
TOTAL	1,343,000			14	30

TABLE 2

Quantities of Supply and Discharge Water, 1976 Season (Preliminary Data)

Permittee	Irrigated Acres	Assumed Irrigation Demand (3.5 AF/ac.)	Supply Measured	 Percent of Assumed Demand	Discharge Measured	 Percent of Total (estimate)
		(acre feet)	(acre feet)		(acre feet)	
Patterson RCD (W)[1]	50,000	175,000	87,000[2]	—	10,000	60%
Mendota-Crows Landing (W)	400,000	1,400,000	930,000	66%	120,000	90%
Turlock I.D. (E)	170,000	595,000	622,800	104%	74,000	30%
Merced I.D. (E)	110,000	385,000	400,000	103%	39,000	70%

[1] (W) denotes "westside" location or west of the river, (E) east of the river.

[2] Data only for June-December, 1976.

TABLE 3

Typical Electrical Conductivities and Suspended Solids of Supply and Irrigation Return Water, 1976 Season (Preliminary Data)

Permittee	Electrical Conductivity Supply Water, (micromhos per cm)	 Irrigation Return Flow, (micromhos per cm)	 Ratio of EC, (return ÷ supply)	Suspended Solids (mg/l) Supply Water	 Irrigation Return Flow
Patterson RCD (W)	850	1230	1.4	119	333
Mendota-Crows Landing (W)	480	1640	3.4	68	218
Turlock I.D. (E)	40	260	6.5	1	7
Merced I.D. (E)	38	224	5.9	7	33

Local Solutions to Drainage Problems

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ABSTRACT

Throughout the San Joaquin Valley the installation of on-farm tile systems can intercept and collect saline subsurface drainage water and thereby reduce or eliminate the damage from high water tables. Five subareas in the San Joaquin and Tulare Lake Basins of the San Joaquin Valley have individually developed local solutions for disposing of saline subsurface drainage water collected within the subareas.

The West side of the San Joaquin Valley has been divided into five different subareas for evaluation of drainage problems depending on the source of irrigation water, access to surface drainage, and the source and quality of subsurface drainage effluent. Each area has an existing subsurface saline drainage problem and some need to better control surface runoff or return flows. The five general areas are located in two distinct basins of the valley — the San Joaquin and the Tulare Lake Basins. See the map in the first paper of this case study. It is anticipated that all tailwater or surface return flows generated in the San Joaquin Valley will eventually be reused within the water-short valley.

The first two areas are in the San Joaquin Basin where the San Joaquin River provides a natural outlet to the Pacific Ocean through the Delta.

The Northern Part of the Delta-Mendota Service Area

The northern part of the Delta-Mendota Service Area has a number of subsurface drainage systems which were installed several years ago prior to any attempts to place water quality controls on agricultural discharges with the collected drainage effluent going directly into the San Joaquin River.

The drainage problem area has increased from a few acres in 1955 to over 60,000 acres with a perched water table less than 5 feet below the soil surface. There are also over 100,000 and 90,000 acres affected by high water tables less than 10 and 20 feet from the ground surface respectively, in this area.

About 60,000 acres of the area now have drainage systems installed which control high water table conditions, and on-farm drainage facilities are being installed continuously.

The quality of the subsurface drainage effluent produced in this area has the lowest TDS of any area in the valley ranging between 1,500 and 2,500 ppm TDS.

The local solution for disposing of the subsurface drainage effluent is the construction of collector systems by local districts with the systems discharging the effluent into the San Joaquin River. The discharges will be removed, however, if and when a valley drain is constructed. Considerable surface runoff or tailwater is also discharged into the river from this area, but that water would not be accepted in a valley drain because the water is of reuseable quality for irrigation.

The Southern Part of the Delta-Mendota Service Area

The southern part of the Delta-Mendota Service Area is also partly drained with subsurface drainage systems. However, most of the drainage effluent produced by these drainage systems is reused by recirculation through open drains and irrigation canals that traverse through the area from the south to the north. Surface runoff or tailwater is also reused with the subsurface effluent several times before all of the runoff finds its way into the Grasslands Water District, a waterfowl habitat area. The Grasslands area takes all of the drainage water

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produced in the southern part of the Delta-Mendota Service Area for flooding waterfowl hunting areas and native pasture. The quality of the subsurface drainage effluent in this area ranges between 2,500 and 9,000 ppm TDS. After all of the reuse, all drainage discharges from the Grasslands Water District eventually end up in the San Joaquin River, which is the source of the agricultural water supply for much of the northern part of the Delta-Mendota Service Area and the Delta areas.

Recently, since more stringent water quality controls for agricultural discharges have been contemplated, one small district has banned the installation of drainage facilities until a suitable outlet, other than the river, can be obtained. The district directors have concluded that no more saline drainage effluent should be mixed with the irrigation water because significant salt balance problems are being created within their district.

The southern three areas are located in the Tulare Lake Basin where very few on-farm drainage facilities have been installed, when compared to the size of the problem area, because there is no natural outlet to the ocean.

Federal San Luis Service Area

The Federal San Luis Service Area has about 300,000 acres that will ultimately need subsurface agricultural drainage. Currently, more than 200,000 acres of land within the area has a perched water table less than 20 feet from the ground surface at this time.

The portion of the area with less than a 10-foot water table increased from about 10,000 acres to almost 120,000 acres between 1967 and 1976.

The quality of the perched water table in this area generally ranges between 6,000 and 15,000 ppm TDS with small areas having salinity concentrations of up to 100,000 ppm. The local solution for disposal of subsurface drainage effluent from this area will be through the use of the United States Bureau of Reclamation's San Luis Drain. This drain which is currently under construction is a concrete-lined open drain with a 300 cfs capacity, and a control reservoir to provide a drainage outlet to the Delta and Ocean.

The Bureau is also presently constructing the initial portion of a drainage collector system for the 600,000-acre Westlands Water District in the portion of the district where the water table is less than 10 feet from the ground surface. The collector system will convey on-farm drainage water from the farms to the San Luis Drain. Each landowner or farmer is responsible for the installation of the on-farm drainage facilities.

Tulare Lake Area

The Tulare Lake Area has a drainage problem area of about 165,000 acres. The only time there is a natural outlet to the ocean from this area is during peak flooding periods of the Kings, Kaweah, and Tule Rivers which flow into the lake area. This is another portion of the valley where only a small portion of the drainage problem area is drained with subsurface drainage facilities because again no collection disposal system has been developed. Where drainage systems exist, all drainage water has been recirculated for reuse as irrigation water systems. Recently, the Tulare Lake Drainage District has constructed a 300-acre pond in the northern part of the district to evaporate subsurface drainage effluent collected by the district. Planning is also underway for the construction of a larger pond in the southern end of the district where all of the district's drainage effluent will be evaporated, and all the salt that is contained in the drainage water will be stockpiled.

The California Regional Water Quality Control Board has established discharge requirements for the northern and southern basins. The local solution for the disposal of subsurface drainage effluent for the Tulare Lake Basin is ponding and evaporation.

Kern County Area

The Kern County area has developed drainage problems from increased irrigated agricultural activities during the last 20 years. The area with the perched water table within 5 feet of the ground surface has increased from about 180 acres to over 22,000 acres in the last 12 years. Crop yield will be reduced due to the drainage problem with resulting substantial income losses with some properties probably being removed from agricultural production. The Kern County Water Agency predicts that unless the drainage problem is solved, the annual damages are expected to increase from $2,665,000 in 1975 to $19,735,000 in 1985 and over $45,000,000 in the year 2005.

The Kern County Water Agency has proposed a local solution for their drainage problem through a project consisting of on-farm tile drainage systems to remove excess water from the crop ground root zone; district facilities to collect effluent from various farms; a main drain to convey the drainage from the problem area; and the use of the collected drainage water for cooling purposes at the proposed San Joaquin Nuclear Project Power Plant. It is projected that under normal operation the cooling towers at the San Joaquin Nuclear Project would put the saline water to a beneficial use and also reduce the volume of the drain water by about 50 percent, helping the disposal problem.

Kern County officials also are investigating the possible use of the drainage water for wildlife enhancement either before or after it is used as cooling water at the power plant and as a potential attraction for industry which can economically utilize concentrated brines developed through additional solar evaporation.

The Wheeler Ridge-Maricopa Water Storage District, which is a member agency of the Kern County Water Agency, has about 6,600 acres of land with perched water table within 5 feet of the ground surface and an additional 17,600 acres with a potential drainage problem that will require on-farm drainage facilities within 10 to 15 years. This district may not be able to wait for the development of a valley-wide or regional system and is considering several of their own local alternatives for disposing of drainage effluent to be collected within the district. They are: 1) local evaporation, 2) disposal through the Kern County Water Agency master drainage program, or 3) a plan to be developed by the San Joaquin Valley Interagency Drainage Program.

SUMMARY

Throughout the San Joaquin Valley the installation of on-farm tile systems can intercept and collect saline subsurface drainage water and thereby reduce or eliminate the damage from high water tables. However, the five subareas in the San Joaquin and Tulare Lake Basins of the San Joaquin Valley have individually developed local solutions for disposing of saline subsurface drainage water collected within the subareas. The northern part of the Delta-Mendota Service Area discharges its drainage water into the San Joaquin River; the southern part of the Delta-Mendota Service Area disposes of its drainage water into the Grasslands Water District where the water is used for irrigating native pasture and wildlife habitat.

The San Luis Drain is being developed to convey drainage effluent from the Federal San Luis Service Area to the western Delta; the Tulare Lake Drainage District is developing evaporation ponds to totally evaporate the drainage water collected in that district; and the Kern County Water Agency is contemplating the use of saline drainage water for cooling the reactors in a nuclear power plant.

A Valley-Wide Solution

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ABSTRACT

The San Joaquin Valley Interagency Drainage Program (IDP) is an action-oriented program with objectives including: 1) coordination of the on-going drainage water management activities of the cooperating agencies (USBR, SWRCB, and DWR); 2) development of alternative plans for managing the drainage waters; 3) determination of potential uses for drainage waters; 4) development of a recommended plan for managing drainage waters; and 5) recommending ways to finance drainage facilities.

Drainage problems in localized areas of the San Joaquin Valley are severe. Yields on individual fields may be reduced as much as thirty percent. The third paper of this case study described the rapid increase in acreage affected by drainage problems. However, on a valley-wide basis only 15 to 20 percent of the potential or ultimate drainage problem area is presently affected. These present drainage problem areas represent only about 4 percent of the valley's irrigated land.

This small percentage on an overall basis makes it difficult to provide a valley-wide or ultimate solution now. Table 1 in the first paper of this case study showed that it would be after the year 2000 before drainage production was half of the ultimate projected. It would be difficult to justify operating facilities at partial capacity for so many years. It would also be difficult to finance the ultimate facilities with this limited repayment capacity while the flows are increasing. Those individuals without problems now are often difficult to convince how severely they will be affected in the future. The relatively small number of people affected now have not been able to convince the legislature to authorize drainage facilities.

Local drainage solutions may not be the long term or ultimate solution. Salts are the problem component of the drainage waters. The salts must be managed and ultimately removed from the valley to provide a salt balance and protect agricultural production.

Planning and implementation must be done now to provide relief for those with existing problems and to integrate any present actions into future and ultimate solutions.

The drainage problem has been recognized for many years. A 1965 report, DWR Bulletin No. 127, "San Joaquin Master Drain", recommended an ultimate solution that was not implemented for the aforementioned reasons. It was decided in 1975 to develop a drainage solution that could be implemented. The San Joaquin Valley Interagency Drainage Program (IDP) was formed by the U.S. Bureau of Reclamation (USBR), the California State Water Resources Control Board (SWRCB), and the California Department of Water Resources (DWR). The IDP objectives include: 1) coordination of the on-going drainage water management activities of the cooperating agencies; 2) development of alternative plans for managing the drainage waters of the San Joaquin Valley, while maintaining agricultural productivity and surface and ground water quality; 3) determination of potential uses for drainage waters; 4) development of a recommended plan for managing drainage waters; and 5) recommending ways to finance drainage facilities.

IDP staff consists of four professionals and two clerical. The staff works with members of each agency to coordinate activities. The staff also meets routinely with a public participation group. The public group represents irrigators, local government and areas under consideration as disposal sites.

IDP is an action-oriented program that will develop recommendations that can be implemented in the near future, as well as an ultimate program. The recommended program may consist of local or regional projects in the first phase and then integration into valley-wide facilities that accomplish salt management and disposal. The recommended San Joaquin Valley Interagency Drainage Program will be developed by the Fall of 1978. Additional time will be required to complete necessary work to upgrade the report so that it can be presented for legislative authorization.

Five basic alternatives are being investigated by IDP. They are: 1) no valley-wide action; 2) evaporation ponds; 3) discharge to the ocean; 4) discharge to the ocean via the San Joaquin River and San Francisco Bay; and 5) discharge to the ocean via the western Delta and San Francisco Bay. Different disposal points are subalternatives within each alternative.

USBR is conducting an economic analysis of the alternatives. SWRCB is conducting an environmental assessment of the alternatives. DWR is developing a financial program and studying legal and institutional constraints. When these studies of the alternatives are completed, the recommended program will be developed. The recommended program may include components from more than one alternative. It will include staging of facilities and reuse of drain water before disposal.

One major difference between IDP and previous studies is that reuse of drainage waters is a primary consideration. The San Joaquin Valley is in an overdraft situation (about 1,500,000 acre-feet per year). Even though the drainage waters are brackish, there are many uses for any water in this water-short area. Potential uses of drainage waters include power plant cooling, marsh development for waterfowl enhancement, recovery of salts, salinity repulsion, and aquaculture.

In addition to reuse, reclamation by desalting is being studied. All the water supplies in the valley are now allocated. A new water development project to import water into the valley would probably cost $150 per acre-foot when the water was delivered. Desalting costs are not much higher than this cost, and the volume of water for disposal would be reduced. One difficulty with desalting is that reverse osmosis does not remove the 10 mg/l of boron in the drainage waters.

Power plant cooling and marsh development appear to be the most practical at this time. Two nuclear power plants are under consideration in the San Joaquin Valley. The timing of construction of these and future power plants may fit with the development of drainage waters. Development of additional marshes would use significant quantities of drainage water. Marshes and power plants might be used in series. The effluent from marshes and power plants would be increased in salinity and would need to be exported from the valley.

Salinity repulsion would take place in the western Delta. Fresh water release is required to prevent sea water intrusion into the Delta. Discharge of drainage waters at the western Delta would reduce the requirement for fresh water to be used elsewhere.

Salt reclamation and aquaculture do not seem too practical now, but are being investigated because they may be in the future. The salt companies are not interested in recovering salt from drainage water because there is more sodium sulfate than sodium chloride. Chemical companies may be interested in individual constituents in the future, but initially the quantities would be too small. Additional study needs to be done before the practicality of aquaculture with drainage water can be demonstrated.

It is important that the recommended program be very flexible with the possibility of changes in technology and the uncertainty of drainage flow projections. At any decision point in the future, the option to change or adjust the drainage program must be available.

Irrigation Return Flow Problems in Yakima Valley

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ABSTRACT

Studies completed in recent years show that irrigated agriculture is a significant source of the pollutants in the lower reaches of the Yakima River. Sediment, phosphates and nitrates are the principal pollutants resulting from irrigation activities. Improved on-farm water management practices should be undertaken to alleviate this water quality degradation.

Since the passage of P.L. 92-500, attempts to apply NPDES permits to irrigation return flows have been stymied by legal questions and a lack of knowledge of relationships between farming practices, soils, weather conditions, and water quality. In addition, there are legal questions regarding the authority of irrigation districts in the State of Washington to control on-farm water management practices.

INTRODUCTION

The Yakima Valley has a total area of 6,062 square miles and occupies the north central part of the State of Washington. About three-fourths of the valley is in the Columbia Basin physiographic province, with the remainder in the Cascade Range. The Cascade Range generally bounds the valley to the west, with the Wenatchee Mountains forming the northern boundary, and Rattlesnake Hills to the east and Horse Heaven Hills to the south separating from the Columbia Valley.

The Yakima River and its tributaries drain the valley. The river heads near the crest of the Cascade Range, northeast of Mount Rainier and flows for 180 miles in a generally southeasterly direction to its confluence with the Columbia River near Richland. It is the largest single river system located entirely within the State of Washington. Major tributaries include the Naches, Cle Elum, Kachess and Teanaway Rivers. The total annual flow leaving the valley under natural conditions would be approximately 3,580,000 acre feet. The actual flow is 2,340,000 acre feet. The average annual irrigation diversions within the basin are 2,365,000 acre feet of which 1,140,000 acre feet are consumed and 100,000 acre feet diverted from the basin.

The climate varies from desert conditions in the lower valley to a moist alpine type in the higher mountains. The irrigated area of the upper valley receives from 10 to 15 inches of precipitation per year, while the lower valley receives less than 10 inches.

Agriculture is the primary economic activity. Yakima is a center for processing of both fruit and vegetable crops grown in the adjacent valleys. There are a limited number of lumber and wood product plants.

Population densities are high in the valleys and low in the surrounding rangelands. The present population is slightly in excess of the 1965 figure of 184,500, and is centered in the towns along the Yakima River.

The first known attempt at irrigated agriculture in the valley was made in 1853 at the Ahtanum Mission near Tampico. In 1867, farmers were diverting water from the Naches River and by 1870 there were 1,000 acres under irrigation in the Yakima Valley. The early systems were privately constructed and served easily accessible lands along the main stem of the Yakima River and the lower portions of the major tributaries.

During 1886-1888 the Northern Pacific Railroad's transcontinental line reached the area and extended over the Cascades to Puget Sound. As it had been granted a considerable acreage in the valley, the railroad and other sources of private capital undertook large investments in irrigation in order to attract settlers. The Sunnyside Canal was started in 1890 to divert water from the Yakima River and by 1892 forty-two miles of canal were completed. In 1900, management was taken over by the Washington Irrigation Company. In the meantime, several other canals were constructed by private capital so that by 1900 the Yakima Valley was the most extensively irrigated area in Washington, with 67,000 acres. This had expanded to 125,000 acres by 1905 when irrigation by the Bureau of Reclamation and the Office of Indian Affairs began.

The Yakima Valley is now one of the most extensively irrigated areas in the United States, having six storage dams, five diversion dams, two hydroelectric plants, six major governmental irrigation projects plus numerous small private irrigation systems and districts. The total area served by irrigation facilities in the valley is approximately 505,000 acres of which 416,000 are served by governmental projects. Water for the remaining irrigable land is supplied through Warren Act contracts and by individuals diverting from small streams. About 18,000 acres are irrigated by groundwater.

Approximately 80 percent of the irrigated area of the valley is watered by furrow or flood irrigation methods. The remainder is sprinkler irrigated except for a few hundred acres of drip irrigation. There is currently a marked trend towards sprinkler systems.

With the advent of irrigation in the valley the quality of water in the Yakima River and its tributaries has declined. Some of the degradation is directly due to irrigation return flows, while further deterioration is associated with fruit processing plants and other agricultural and industrial enterprises attracted to the valley by the strong irrigated agriculture base.

In the upper reaches of the valley, water quality is virtually unimpaired. Although mineralization increases more than four-fold in going from the headwaters to the mouth, the water still remains in the low salinity class and is suitable for reuse as irrigation water. The main effect of irrigation activities is high concentrations of suspended sediment, phosphates and nitrates.

Suspended solids in return flows settle and interfere with drain design flow capacity and cause wear of pumps and sprinklers. Where discharged to the river, they settle behind diversion structures and require periodic removal. Associated with the sediment is attached phosphate which frequently reaches levels in the lower river above the potential algal bloom limiting concentration. Similarly, nitrogen levels, which are a consequence of the percolation of irrigation water applied in excess of crop needs, greatly exceed the potential algal bloom limiting concentrations in the lower river. Heavy growths of plankton and higher forms of aquatic life are consequently found in the river from Wilson Creek, a few miles below Ellensburg, to the mouth. The photosynthesis and respirational activities of these organisms cause a wide diurnal fluctuation in several water quality parameters including dissolved oxygen, pH and alkalinity.

Federal and State Irrigation Return Flow Activities

Federal Water Pollution Control Act Amendments (P.L. 92-500)

The Federal Water Pollution Control Act Amendment of 1972 (P.L. 92-500) was the most far-reaching water pollution legislation ever undertaken by Congress. The ramifications of its passage began to be felt immediately. However, debates on its intent and applicability were to continue as its various programs were undertaken. Some debate has been resolved through judicial processes. Much debate will continue among and within administrative agencies as they struggle with interpretation of the legislation. In the agricultural pollution area, the intent of the Act was less clear than with other segments. After four years of interpretation, both by the courts and involved agencies, the struggle continues as to how to carry out the intent of Congress in the agricultural sector.

The potential for pollution from agricultural lands was mentioned in the Act under two specific headings. First, Section 304 required from EPA information and "guidelines for evaluating the nature and extent of nonpoint sources of pollutants" and "processes, procedures and methods for control of pollution" resulting from agricultural activities (among others). Section 208 of the Act required, as an element of area-wide planning processes, the identification of agricultural related nonpoint sources of pollutants. This section also required identification of procedures and methods to control these sources to the extent feasible.

The Act had one other connection to return flows from irrigated lands. Section 502 — general definitions — defined a point source as "Any discernible confined and discrete conveyance, including, but not limited to, any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, . . . from which pollutants are or may be discharged."

Point sources were to be treated quite specifically and in their own particular manner. Section 402 of the amendments spelled out the details of a NPDES program which would place dischargers of pollutants from point sources under increasingly more stringent limitations. The goals of the Act were rather ambitious — such as the 1983 goal of "fishable and swimmable" waters. Large portions of the Act were devoted to spelling out the details of the NPDES program. Looking back, it is apparent that discharges from industries and municipalities via pipes and ditches were seen as a major threat to the nation's water quality. From all that has been seen of the NPDES program, it has had the most significant effect with the treatment of sources with discrete processes. It is also apparent that, in addition to process changes, end of the pipe effluent treatment was seen as a major tool in improving water quality. Along with funds for sewage treatment plant construction and upgrading, research and planning, the NPDES program was one of the major tools provided for the attainment of the ACT's ambitious goals.

In spite of all the above, it remains a fact that the only specific referral to agricultural return flow was as a nonpoint source. These sources of pollution were to be treated under the results of long-term planning — specifically that of Section 208. On the other hand, the administrating agency, the Environmental Protection Agency (EPA), could not ignore the definition of point source and their mandatory treatment under the NPDES permit program.

In December 1972, EPA began to solicit information concerning the types of agricultural point sources which would come under the NPDES program. The result of these activities were regulations pertaining to agricultural point sources published July 5, 1973. These regulations as they apply to irrigation return flows, attempted to exempt what EPA considered to be the less significant portion of dischargers.

> NPDES requirements apply to discharges of irrigation return flow (such as tailwater, tile drainage, surfaced groundwater flow or bypass water), operated by public or private organizations or individuals, if: (1) there is a point source of discharge (e.g., a pipe, ditch, or other defined or discrete conveyance, whether natural or artificial) and; (2) the return flow is from land areas of more than 3,000 contiguous acres, or 3,000 noncontiguous acres which use the same drainage system.
>
> It is the individual or organization who actually has control of or responsibility for the discharge of irrigation return flow who must apply for a permit. For example, if water is supplied by an organization but the discharge of return flow to navigable waters is controlled by an individual who has more than 3,000 acres under irrigation, it is the individual who must apply for a permit. On the other hand, if an irrigation organization supplies and controls the irrigation return flow from a total of 3,000 acres to navigable waters, the organization must apply for a permit, even though one individual may be supplied with water for 3,000 acres or more.

The initial regulation did not specifically state the individual or organization who was to receive the permit. However, because of their legal powers and size, it was obvious that irrigation districts were the planned recipients.

The interpretation of the above paragraphs was to determine the extent to which Washington's irrigated agricultural lands would be affected. For instance, if all irrigation districts over 3,000 acres received permits, approximately 94 percent of Washington's irrigated land would be affected. If, on the other hand, those districts with 3,000 acres draining to one discharge were permitted, then at the most 70 percent of the irrigated acreage would have been affected.

Three Major Issues

The details of which districts were to receive permits was to be one of three primary issues. A second of the major issues also pertained to the districts — it was whether any irrigation district had the authority over, and responsibility for, irrigation return flows. The third issue pertained to the 3,000-acre limitation and EPA's authority for granting exemptions to certain categories of point sources.

1. Irrigation districts in Washington receive their authority to operate under Chapter 87 Revised Code of Washington. The purposes of irrigation districts are rather clearly enumerated in that chapter, and among those purposes and powers are those of construction and maintenance of delivery and drainage "systems". Also, districts are granted the power of assessment for costs of operation of such systems. In relation to specific delivery systems, the district's control terminates at "the point of individual distribution". Because the point of control and authority specifically stops at the point of individual distribution, districts argued that they had no control over the manner in which an individual managed his water. This has been (and is) a major obstacle to acceptance of the permit concept by districts.

2. Also at issue is the question of whether or not districts have the authority to operate "systems" for pollution control. RCW 87.03.120 and 87.03.125 grant the authority for operation of sanitary sewage or drainage systems by a district when it "is of special benefit to the lands of a district as a whole". It seems then that districts have the power to operate the facilities for pollution control and the maintenance of "systems" is left for interpretation.

It appears that the powers of pollution control (although not specifically termed as such) and assessment are available. However, three more subtle questions result from this observation: 1) Is "end of the pipe" pollution control cost-effective or socially acceptable? 2) With a pollution control and assessment system within the district, could the political structure of the districts survive? 3) Can assessments be made to those (the poorly managed farms) within the district who receive district services?

The former two questions will be dealt with in a subsequent portion of this discussion; however, to the latter question, it should be pointed out that irrigation districts routinely utilize their manpower and machinery to carry out pollution control construction and maintenance for individuals. They also routinely assess those individuals for a portion of the cost incurred (e.g., construction and cleaning of sediment basins).

3. A third major issue was developing at the time EPA formalized its regulations on agricultural point sources. This issue was that of EPA's authority for the 3,000-acre exclusion. The 3,000-acre limitation apparently was placed in the regulation for two reasons: 1) To minimize the workload by State agencies and EPA by minimizing the number of permits issued, and at the same time, 2) To focus governmental resources toward the major portion of the problem. According to EPA estimates, 80 percent of lands irrigated by irrigation districts or similar irrigation organizations fell within the 3,000-acre criteria.

The Natural Resources Defense Council (NRDC) took exception to the July 5, 1973 agricultural regulations by filing an action with the District Court in Washington, D.C. Their exception was based on their opinion that the Law (P.L. 92-500) provided no authority for exclusion of point source discharges from the NPDES permit system. Secondly, the NRDC felt that a significant source of pollutant loading could come from operators under 3,000 acres.

Washington State's Involvement

It was not until November 1973 that the Washington State Department of Ecology (DOE) accepted the responsibility for administration of the NPDES program. Transfer of the agricultural portion of that program was completed in July of 1974. At that time, none of the major issues had been resolved. Further, opposition was becoming formally organized and battle lines were forming.

The DOE quickly developed a scheduled program for obtaining NPDES applications and issuance of permits. Although program planning got off to a flying start, the program quickly fell behind schedule because none of the major issues had yet been resolved.

With pressure to get the program moving, the DOE sought the guidance and advice of entities concerned with water and skilled in the area of irrigation. This took place with the formulation of a State Technical Advisory Committee for Water Quality Improvement (TAC). Formation of this group took place in September 1974, and agencies and organizations which took part were: U.S. Geological Survey, U.S. Soil Conservation Service, U.S. Bureau of Reclamation, Washington State University, Washington Association of Conservation Districts, Washington Reclamation Association, State Association of Washington Irrigation Districts, and the Department of Ecology. The initial tasks of this group were to review the problems of application of the NPDES permits to irrigated agriculture and to provide input to the content of the proposed permits.

During the first eight months of DOE's administration of the agricultural permits, some applications were received and, with the guidance of the TAC, these applications were processed. The process was carried out to the point of "legal notice," but the proposed permits were not issued. Several districts refused to submit an application. However, those who did submit applications submitted them only for those facilities for which they felt they had control (operational wasteways).

In early 1975, the NRDC received a favorable judgment regarding the 3,000-acre limitation. The Court ordered EPA to draft and promulgate a new set of regulations relating to irrigated agriculture and gave them one year to complete the task.

At this point, the TAC should have been dissolved, but there remained the spirit of cooperation, awareness of the agricultural pollution problem, and the momentum toward a positive approach to abatement of these problems. The TAC was to remain intact and active for over a year after the NRDC decision. In fact, it was this group, with the attributes mentioned above, that was responsible for guiding initiation of the Sulphur Creek project.

Water Quality in the Yakima River Basin

As part of its statewide water quality planning efforts, the DOE, in 1973, undertook the development of a water quality management plan for the Yakima Basin. The basis of this plan was to be developed through contracts to the consultants CH2M-Hill (CH2M).*

A portion of the report from CH2M dealt with a current characterization of water quality in the Yakima Basin. This report evaluated sources of pollutants entering the Yakima River. CH2M conducted its own monitoring but also relied extensively on existing data. A map of the Yakima River system is shown in Figure 1 (CH2M). Figure 2 (CH2M) shows the results of its source load evaluation. From this overall view, it can be seen that the Yakima River below Sunnyside Dam (the diversion structure for the Sunnyside Valley Irrigation District) is degraded, largely due to the impact of irrigation activities.

The preface of the characterization report states that information "clearly indicates agriculture as a significant source of pollutants," and further, "any attempt to improve the quality of the waters in the Yakima Basin must make considerable efforts to improve the quality of return flows." The emphasis on return flows follows from an estimate that in an average year, 80 percent of the summer flow below the Sunnyside Dam to the mouth of the Yakima River is attributable to return flows.

Following completion of the water quality management study, the DOE again contracted with CH2M to look at agricultural return flow management in the State. The objectives of the study were as follows:

1. Determine the relative contribution of point and nonpoint sources to water quality degradation in a predominantly agricultural area.

2. Determine alternative methods of reducing or eliminating the addition of wastes from these sources to water bodies.

3. Identify institutional constraints on applying the NPDES permit program to return flow management.

4. Recommend methods of applying the NPDES permit program to feedlot and irrigation return flows to result in improved instream water quality.

CH2M conducted the study in three phases. The first phase was a detailed study of the Sulphur Creek Drainage, a subbasin within Washington's Yakima Basin. The second phase was a semidetailed study of the Sunnyside-Roza Area of the Bureau of Reclamation's Yakima Project. In the third phase, the results of the first two phases were applied to the entire Yakima Basin.

Results of the study pointed to improvement of on-farm management practices as the initial step in improvement of water quality in the Yakima. Sediment, phosphates, and nitrates were the principal causes of degradation from irrigation activities. For instance:

1) Phosphate losses in some areas were as high as 40 lbs/ac/yr,

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*CH2M, "Characterization of Present Water Quality Conditions in the Yakima Basin," Department of Ecology, February 1975, and CH2M "Agricultural Return Flow Management in the State of Washington," Department of Ecology, April 1975.

2) Nitrogen losses were as high as 30 lbs/ac/yr — up to 20 percent of that applied — Nitrogen concentration in the lower Yakima has increased five-fold over the last 20 years, and

3) Cleaning sediments from the drains in the Sulphur Creek basin alone cost $65,000/year — up to 190 tons per day are transported from the Sulphur Creek drainage to the Yakima River.

In the institutional area, the report pointed out that it is unfortunate that our current water rights system "does not encourage better management of our water resources" (CH2M, page 10, Summary Report).

Nevertheless, living within our present legal framework and with the need of addressing the NPDES permit system, the report suggested the following guidelines for any program developed to meet current needs:

1. Recognize that individual farm operations are the significant cause of pollution in irrigation return flows. The strategy should be geared to ways of improving on-farm practices. The initial emphasis should be on the small percentage of farmers responsible for the majority of the problems.

2. The irrigation districts must play a major role in seeking solution to water quality problems by identifying problem areas, im-

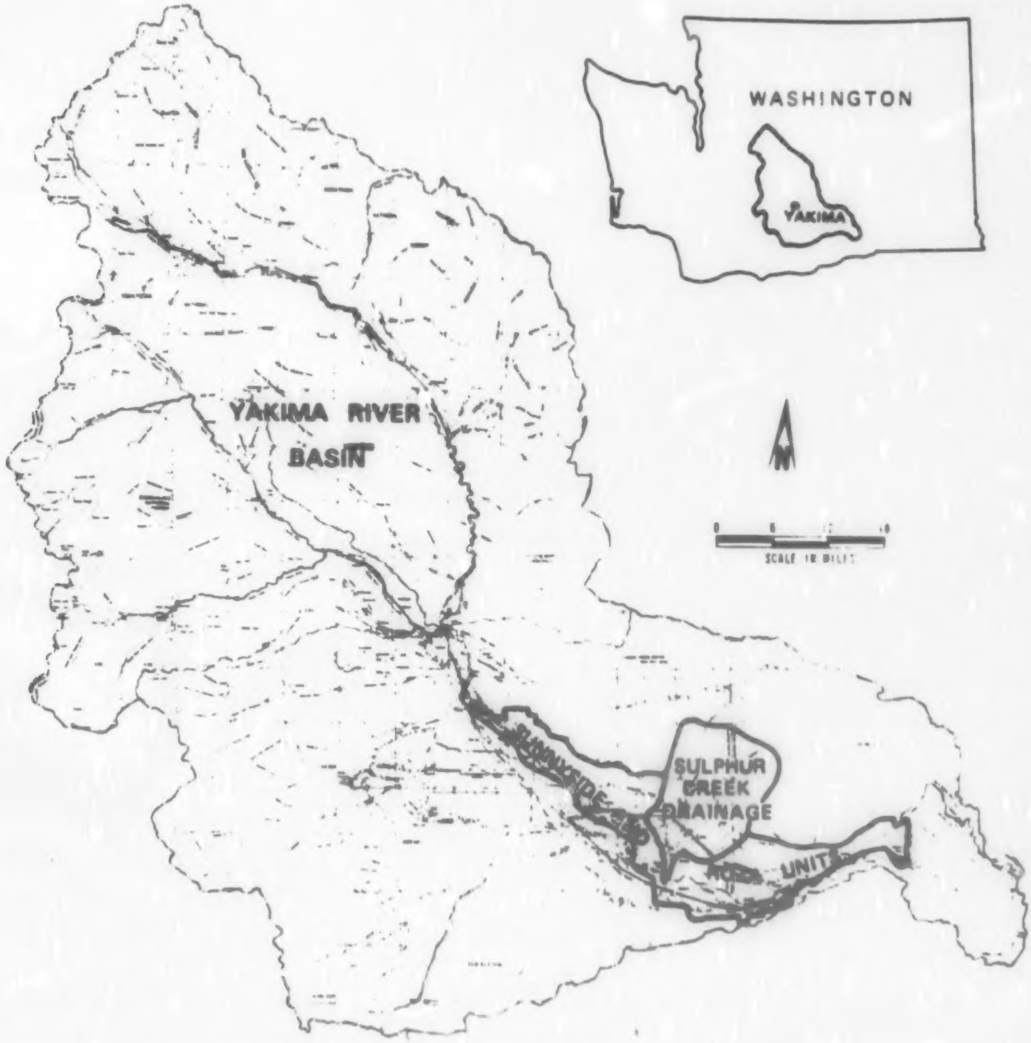

Figure 1. Map of the Yakima River system.

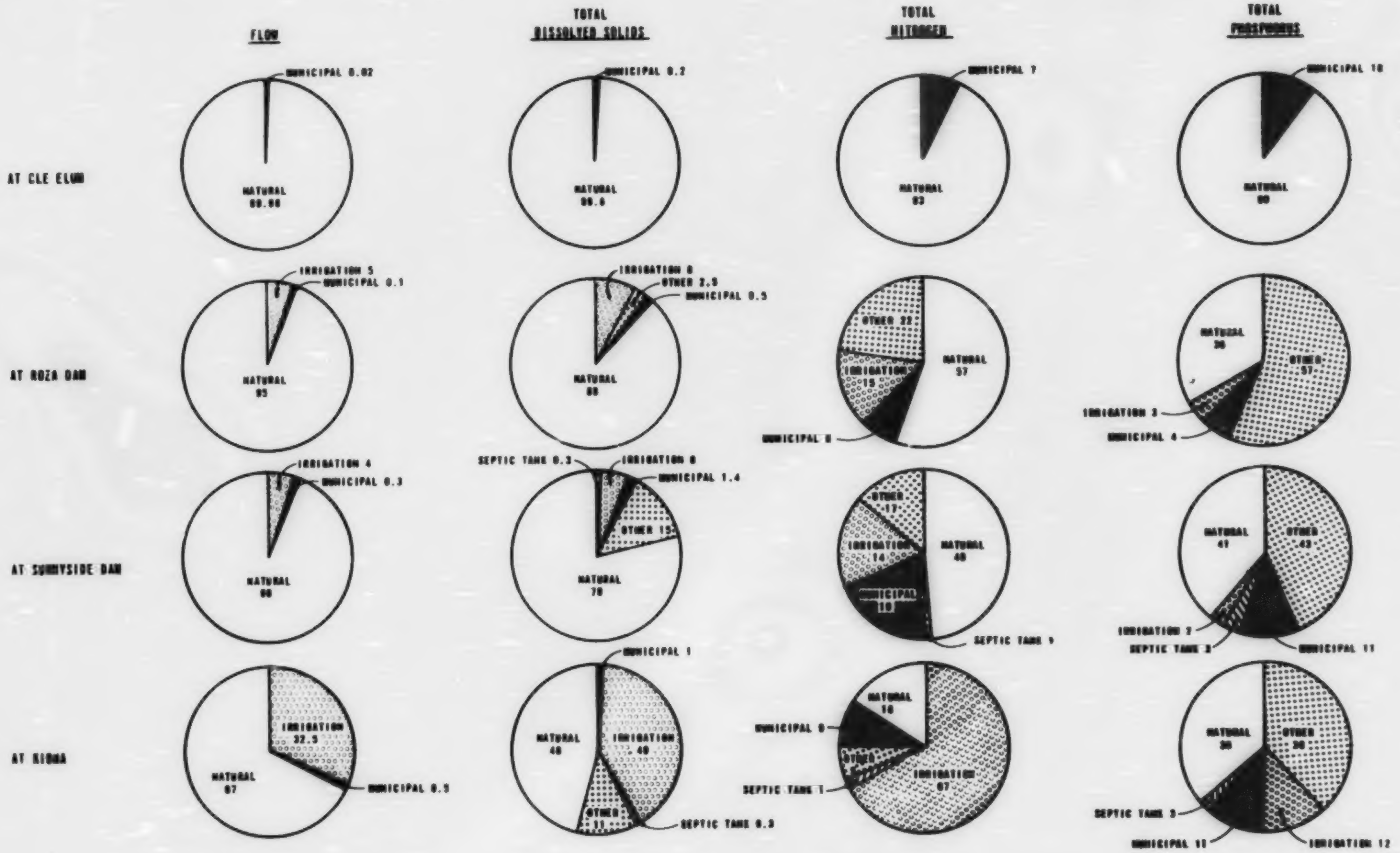

Figure 2. Sources of pollutants in the Yakima River. Values are expressed in percent.

proving water deliveries, and encouraging better water management.

3. Statewide and regional advisory committees could be an effective way to assist the DOE in developing and implementing a pollution abatement program for irrigated agriculture.

4. The basin approach to improving water quality should be through an education program designed to assist individual farm operators. The Bureau of Reclamation, the Soil Conservation Service, and Washington State University have developed programs encouraging better on-farm water management.

5. Water quality monitoring should be continued and should be designed to measure long-term quality changes. Quantity measurements should be an integral part of all quality measurements. (CH2M-1975).

In all of the work that has been completed or is underway concerning agricultural pollution abatement, there seems to be three general topics: 1) legal frameworks, 2) technical alternatives, and 3) the socio-economic realities (institutional frameworks). The broad nature of these topics in itself points to the complexity of the problem. It is apparent that any long-range solution to pollution from irrigated agriculture must deal with all of these aspects. However, as a beginning, the Sulphur Creek project was developed to deal mainly with the technical and socioeconomic factors.

The Sulphur Creek Pilot Project: A Practical Approach to Control of Pollutants Leaving Irrigated Farmlands

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ABSTRACT

The Sulphur Creek project grew out of the momentum and confusion resulting from attempts to apply a National Pollution Discharge Elimination System (NPDES) permit to irrigation return flows. The result has been a project containing what appeared to be compatible and, for the most part, admirable objectives — soil and water conservation, improved water quality, improved fertilizer and pesticide application, improved crop production, and local control. Along with education and technical assistance for the individual farmer, this unique program is structured to provide local control to decisions affecting the farmer. The Best Management Practices concept assumes that informed decisions and improved management will generally provide improved crop production, conservation of soil resources, and cleaner water.

The project is currently just over one year old. Details of the technical success of the project will not be available for some time. Unlike most types of industry covered by the NPDES permits, irrigation return flow improvement represents complex hurdles which have to be overcome by facing the realities of technology, politics, economics, and social patterns.

Description Of Area

Sulphur Creek (Figure 1) is a perennial tributary to the Yakima River, draining over 48,000 acres near Sunnyside, Washington. Two major irrigation districts (Sunnyside and Roza) cross this drainage.

Major crops grown in this area include mint, sugar beets, corn, hops, tree fruit, and small grain. Total crop value exceeds $46 million annually.

Within Sulphur Creek, there are about 550 farm operators. A 1974 study of this area found that these farmers receive an average of 584 cubic feet/second (cfs) of water during the irrigation season. Of this, approximately 208 cfs is returned to the Yakima River, about 35 percent of the total delivery. These return flows carry with them an average of 190 tons of soil per day. Sulphur Creek is the most significant drainage to the Yakima River in terms of sediment load, as shown in Table 1.

Conceptual Framework

Soon after the NRDC versus EPA decision was entered (March, 1975), the Department of Ecology (DOE) and the State Technical Advisory Committee for Water Quality Improvement (TAC) were wrestling over how to deal with the 12-month lull while new regulations were developed. The momentum generated through the TAC was positive and forward in nature. It was not surprising that through this group the idea of a state pilot project developed.

Sulphur Creek began with discussions between the U.S. Soil Conservation Service (SCS) and DOE concerning possibilities of in-

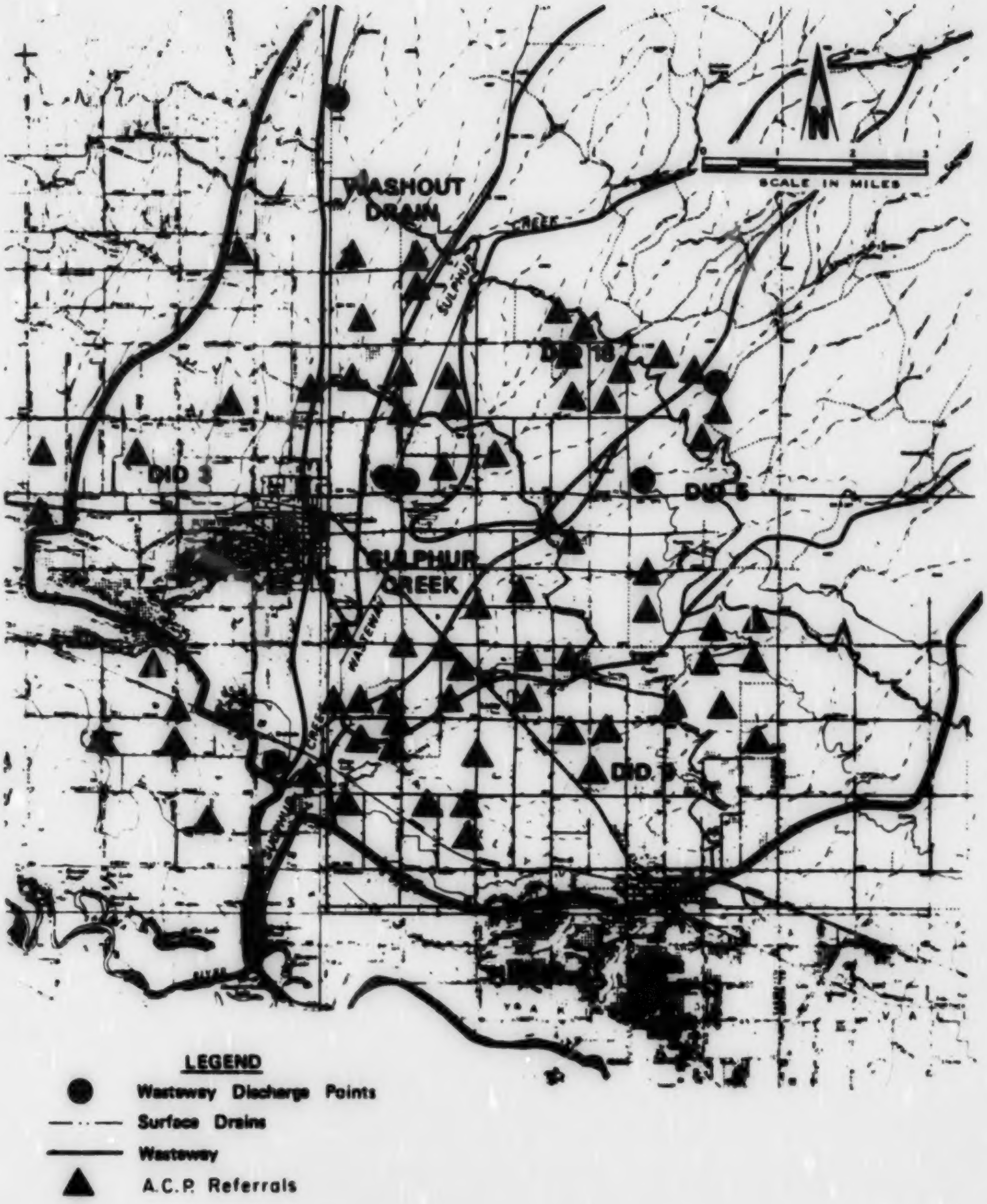
N
0 1 2 3
SCALE IN MILES
WASHOUT DRAIN
SULPHUR
DID 18
DID 3
DID 5
SULPHUR CREEK
WASTEWAY
CREEK
DID 9
RIVER
LEGEND
Wasteway Discharge Points
Surface Drains
Wasteway
A.C.P. Referrals

Figure 1. Sulphur Creek drainage area. The abbreviation "DID" refers to "Drainage Improvement District."

TABLE 1

Comparison of Major Drains in Yakima Basin
(Average values for 1974 irrigation season)

	Measured Parameters	Sulphur Creek @ Green Valley Rd.	Granger Drain @ Highway 223	Spring Creek @ Hess Rd.	Snipes Creek @ Old Inland Empire Rd.	Wilson Creek @ Canyon Road	Wide Hollow Creek @ Washington Ave.	Moxee Drain @ Birchfield Road	South Dr. @ Highway 22 Near Satus	Marion Drain @ Highway 97
	Flow (cfs)	310	28	34	40	135	24	32	69	224
	Temperature ($^{\circ}$C)	13	15.2	16.5	16.8	13.0	14.6	16.8	14.9	13.3
	Dissolved Oxygen (Mg/L)	10.0	6.8*	8.1*	8.0*	8.3	8.2	7.4	8.2	8.8
	pH (Units)	7.6	7.7	7.8	7.8	7.8	8.0	7.7	7.8	7.6
	Conductivity (Micromhos/cm)	261	404	299	193	230	288	372	412	281
Bacteria	Total Coliform (Count/100 ml)	35,000	40,000*	1,700*	3,200*	6,500	1,800	-	-	-
	Fecal Coliform (Count/100 ml)	2,800	1,600*	860*	260*	770	160	-	-	-
	Cod (Mg/L)	13	22	14	10	14	14	17	15	10
Nitrogen -N	$NO_3 + NO_2$ (Mg/L)	1.80	1.64	1.23	0.25	0.38	0.65	0.81	1.68	2.30
	Kjeldahl (Mg/L)	0.59	0.80	0.40	0.29	0.42	0.52	0.60	0.61	0.42
Phosphate -P	Ortho-P (Mg/L)	0.15	0.18	0.06	0.03	0.09	0.09	0.16	0.10	0.08
	Total P (Mg/L)	0.45	0.54	0.25	0.16	0.15	0.12	0.40	0.22	0.13
	Suspended Solids (Mg/L)	229	157	87	84	20	13	134	48	20
	Turbitity (J.T.U.)	73	42	32	27	7	3	30	17	[illegible]

* Samples not taken over entire irrigation season.

teragency cooperation in a program of agricultural pollution abatement. These discussions culminated in submission of an issue paper to the TAC by the Washington Association of Conservation Districts (WACD) and the SCS. This paper specifically dealt with the conservation districts' proposed role in the NPDES irrigation return flow program. Calling for Conservation District (CD) and SCS assistance to both DOE and the farmer, the paper outlined a proposal whereby farmers could complete the traditional conservation planning process and, in that way, meet the requirements of the State from a water pollution control standpoint. In the conservation planning process, a particular farm unit is evaluated against current technology and recognized conservation practices. Following evaluation, the individual farmer is provided a list of alternative pathways which, when carried out, would get him from where he is today to conservation farming at some point in the future. This type of planning process contained all of the flexibility and local considerations thought necessary for a successful program in pollution abatement for irrigated agriculture. Conservation districts (CD) and the SCS also offered their assistance in the implementation of conservation plans and with the recording and documentation processes that would follow. The initial paper presented to the TAC recognized the need for information/education. It called for full utilization of the Washington State Cooperative Extension Service's capabilities in informing the farmer of current technology.

After considerable discussion, a final project proposal was prepared by the DOE utilizing the WACD/SCS issue paper as a basis. The following is a description of how that program was to work:

1. The proposed program for the Yakima Valley was not a study but an operational program for decreasing erosion on the farm and reduction of associated adverse water quality effects. Results were to be accomplished by providing better management practices while considering the individual farmer's goals. Also, this program was to promote refinement of water delivery and return systems within irrigation districts which would complement the on-farm effort.
2. The on-farm portion of the program was to be a joint SCS, CD, irrigation district (ID), farmer endeavor which would result in a farm plan. This plan, when certified by the Department of Ecology, would assure the farmer that he would be in compliance with water pollution laws and was using the best reasonably available technology according to his individual circumstances.
3. The program was to begin with a valley-wide public information release which would explain the reason for the program and the elements of the program.
4. The Operations Committee (a group of local irrigation/conservation specialists) was to consider problem areas in the valley from information supplied by SCS, irrigation districts, and DOE and was to designate a priority list of problem areas. These areas were then to receive a more intense public information effort which would explain in detail the program and alert farmers to the arrival of SCS specialists.
5. The most important facet of the program was that the farm plan was to be designed by the farmer himself to fit a particular farm. Technical help was to be provided by the SCS specialist as he and the farmer worked together developing each plan.
6. Following the intense information program, the SCS specialists were to begin calling on farmers to begin developing farm plans. The resulting plan would be reviewed by the local conservation district, and, if acceptable, the local district would recommend certification by the Department. The certified plan was to indicate that the farmer would be using the best available technology and would be in compliance with Federal and State water pollution control laws.
7. Implementation of the plans was to begin prior to the beginning of an irrigation season with technical help from the SCS, CD, or irrigation district. These plans would be written for periods of time ranging from three to ten years, depending on each individual's desired goals and economic capabilities. The SCS would assess all implemented plans and would submit to DOE an annual summary of progress. Each CD was to maintain records of developed farm plans. These records would be available to DOE as necessary for review.

8. The order or priority to be used by SCS personnel when entering a "problem area" was as follows:
    a. Work with those individuals who were interested, would cooperate voluntarily, and could accomplish improvements without major investment requirements.
    b. Work with those individuals who would cooperate voluntarily but would require some cost sharing for structural or other improvements. These could be identified initially and bypassed until cost-sharing funds are located.
    c. Identify those individuals for appropriate enforcement action who were refusing to cooperate.
9. All farmers in a "problem area" would not necessarily require a farm plan for corrective action. Those farmers who were managing their operations responsibly were to be identified to the CD by SCS and bypassed.
10. The scope of this program was, ideally, the entire Yakima Valley. Initial funding limitations precluded this broad geographic scope and indicated concentration of the effort to, perhaps, the lower Yakima Valley (Granger-Sunnyside vicinity), where most indicators suggested the greatest problem existed. If additional funds became available, the program could easily be expanded to include other "problem areas" in the valley.
11. The SCS and CD's have worked successfully with this approach for 40 years with those who would cooperate. The past approach had been strictly voluntary. It was envisioned that eventually a regulation might be developed which would specify the need for management plans in those areas where voluntary effort had not been successful. Such a regulation would provide for a certification procedure which would assure farmers with certified plans that they are in compliance with water pollution control laws.

The basic concepts of this approach are illustrated in Figure 2.

Project Initiation

The initial steps in getting a project such as Sulphur Creek underway included organization of the Operations Committee, orientation of the technical staff, and the gathering of available information.

The initial meeting of the Operations Committee was held in June 1975, and the actual Committee membership included the following:

Conservation Districts — Four members
Irrigation District Boards — Three members

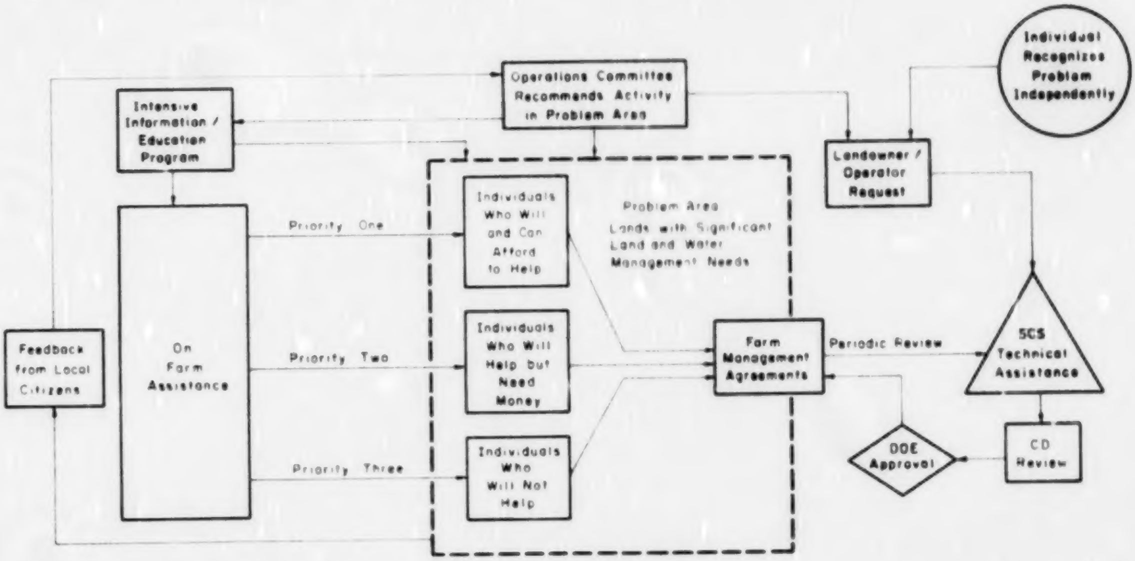
Operations Committee Recommends Activity in Problem Area
Individual Recognizes Problem Independently
Intensive Information / Education Program
Landowner / Operator Request
Problem Area
Lands with Significant Land and Water Management Needs
On Farm Assistance
Priority One
Priority Two
Priority Three
Individuals Who Will and Can Afford to Help
Individuals Who Will Help but Need Money
Individuals Who Will Not Help
Feedback from Local Citizens
Farm Management Agreements
Periodic Review
SCS Technical Assistance
DOE Approval
CD Review

Figure 2. Flow chart for implementation of the Sulfur Creek Pilot Project.

U.S. Bureau of Reclamation (Yakima Project) — One member
Bureau of Indian Affairs (Wapato Irrigation District) — One member
Cooperative Extension Service (Yakima County) — One member
U.S. Corps of Engineers (Seattle) — One member
Department of Ecology (Yakima Office) — One member

This management team was formed to provide local control. The purpose of the Operations Committee was to make the farm plan concept work. The 12 members who made up this Committee were, for the most part, local to the Yakima Basin and intimately involved in irrigation and farming activities.

The Committee was charged with the tasks of 1) giving general guidance to the program, 2) determining areas of need for the program, and 3) acting as a coordinating body between the individual farmers and governmental agencies. In this way, the Committee has provided local representation with the best interest of the individual farmer and the environment under consideration.

Details of funding for the project also had to be worked out in the early months. The DOE and the SCS both agreed to contribute $100,000 for the initial two years of the project. The majority of this $200,000 funding was to provide technical assistance to the farmers. The actual contract between the SCS and DOE took longer than expected to be developed. It wasn't until mid-1975 that the papers were signed and the project was ready to go.

The Operations Committee went quickly to work and identified Sulphur Creek as the initial target area for the Yakima program. However, it was August, and the irrigation season was essentially completed in 1975 before the SCS technical staff was identified, familiarized with the area, and ready to begin development of farm plans.

During this organizational period (June through August, 1975), the Operations Committee was thoroughly updated as to the status of regulations under P.L. 92-500, the mechanics of the program, and Yakima River water quality data (principally CH2M studies). After reviewing the available water quality information and gaining an awareness of the limitations in manpower, the Operations Committee decided to more narrowly focus its attention to subdrainages within the Sulphur Creek drain. Drainage Improvement Districts 5 and 18 were selected (Figure 1).

In the initial selection of an area, several strategies were considered. For instance, the Committee could have selected an area farther upstream, such that improvements in sediment load to the Yakima River would be more visibly seen. This strategy was appealing, because it was felt that if individuals could see visible improvement in river water quality there would be more of a tendency to gather behind and support the program. However, as time progressed, it became apparent that the Operations Committee made the right choice. With Federal regulations pending, it was obvious that it would eventually be necessary to document the results of the project in terms of water quality data. The previous study in the Sulphur Creek area by CH2M-Hill provided most of the needed background data. Monitoring programs were to be developed to follow up previous work and so that the results of this type of program could be adequately assessed.

When Sulphur Creek was identified as the target area, work by the SCS technical staff began. There were no published soil surveys available at that time, so that the staff went to work developing a "mini" survey for the area. Soil series were identified, descriptions obtained, and aerial photographs accumulated. These, along with other pertinent and up-dated sections of technical handbooks containing systems specifications, irrigation guidelines, and minimum conservation practices, were gathered to formulate a planner's handbook, specific to Sulphur Creek.

The SCS technical staff consisted of four people of varying experience. In spite of their technical experience, there was a need to become orientated with the irrigation techniques of the area and the topography of Sulphur Creek. A week-long training session was organized by the SCS personnel for Sulphur Creek staff and for any interested irrigation district personnel. Representatives from both major irrigation districts attended (Sunnyside Valley Irrigation District and the Roza Irrigation District). The session covered such items as theory and computer capabilities for soil intake values and irrigation efficiency. Field evaluations were made of rill systems, including analysis of soil moisture and intake rates.

Information and Education Program

It was recognized that if a program aimed at changing on-farm management practices was to succeed, it would be necessary to accomplish two tasks: 1) Raise the level of general awareness in the farming community as to the technical and financial opportunities available; and 2) Inform the farming community of the goals and framework of the project. Virtually all types of media were utilized. Although a planned and corrdinated approach was needed, efforts to develop such a program never succeeded.

Prior to SCS staff actually contacting any farmers, a color brochure was developed. Input into the contents of the brochure was received from the State Technical Advisory Committee (TAC) and the Operations Committee. Specific effort was made to insure that the message to the farmers was clear and to the point.

Initial intentions were to have a valley-wide approach and to mail the brochure to all irrigation district members in the Yakima Valley. Valley-wide coverage of the project was inevitable, due to the major newspaper distribution and TV/radio transmission areas. However, the attempt to cover the entire valley with limited resources lead to the initial mistake of not giving the project a consistent image and name. For example, the initial project was titled "The Yakima Basin Farm Plan Program". The title of the brochure, "The Yakima Basin Farm Plan," was slightly different. When emphasis shifted to the Sulphur Creek area, the program then became "The Sulphur Creek Pilot Project", "The Sulphur Creek Project", etc. In this transition, the basic goal of name familiarity was lost.

By the time the color brochure was ready to mailing, it was decided that the initial information effort should be geared more intensively to the target area — Sulphur Creek. Time constraints forced limitation of the initial mailing to operators in Drainage Improvement Districts (DID). The Roza and Sunnyside Valley irrigation districts agreed to mail the brochure in a special mailing with a conservation district cover letter to these people. Controversy arose over the wording of the cover letter and, consequently, only partial cooperation with the the irrigation district was achieved. Nevertheless, the general mailing was made to DID 5 and 18 farmers, with agreement of the irrigations districts that a future mailing of the brochure would be made valley-wide with irrigation district year-end water statements.

Prior to the time of the first mailing of the brochure, it was apparent that farmers were not going to "break the door down" to get involved in the program. Consequently, the conservation district cover letter was written to invite operators to a public meeting at a local Grange Hall in August of 1975. Members of the Operations Committee spoke at the meeting and reaction appeared favorable. Something above 20 percent of the 200 operators in DID 5 and 18 attended this session. No specific yes/no requests were made during the session in terms of cooperating with the project.

As the project was undertaken, several news releases were made through the local news media (newspapers, radio, and TV). Spinoff coverage of the project developed through the existing controversy over the NPDES program and through visits to the area by EPA personnel.

Adding to this type of news coverage, news articles were developed by the SCS personnel on the project as one of their job requirements. Timely and well-written articles were developed and received favorable coverage by farm journals.

In preparation for public meetings and presentations, a slide show was prepared. This show, with minor modifications, is still being utilized to publicize the project.

Another mechanism used for general information was the development of a poster. The theme presented was "Are You Losing More Than You're Using." The title was accompanied by a two-color sketch of an eroded field.

Over the first year of the project, there has been an effort to promote tours in the Sulphur Creek area so that public awareness might be increased. Guided bus and car excursions around the basin with conservation district representatives, irrigation district people, administrative (EPA) personnel, and farmers has helped to show the effect of rather simple conservation practices on water quality.

Unfortunately, the level of information/education never became anything more than a general awareness program. In other words, the more or less intensive information and education effort was never a reality. It should be noted, also, that almost the entire effort was informational in nature and not educational. For a variety of reasons, educational productions were limited. It has been apparent that awareness of the program does not alone commit people to it.

The problems in the information/education effort were seen early in the project. Responsibility for the program was not defined even though efforts were made by DOE and SCS to divide and more clearly define responsibilities. At the onset of the program, an information and education schedule was developed for discussion, but this schedule contained no financial commitments or constraints. Consequently, in the first crucial months, information attempts were following an unrefined schedule with undefined financial needs or abilities.

Six months after the Sulphur Creek crew was on the ground, several alternatives to the information/education levels were developed with budgets. It was DOE's responsibility to find the funds for the effort. One such proposal, having a budget of $20,000 for the remaining 18 months of the project, was selected. Nevertheless, funds of this magnitude were never located.

In February of 1976, $5,000 was located in the SCS contract funds and a program was developed around that figure. Posters, slide shows, and educational brochures were listed as major expenditures. Nevertheless, without the information and educational responsibility clearly located, this program has only been partially carried out. Additionally, it should be noted that the intensive effort which was planned for the first crucial months of the project was lost and not recoverable.

Farmer Contact and Farm Management Agreements

Following formation of the Operations Committee, orientation of the technical staff, selection of Sulphur Creek, and initiation of the information/education effort, work began in soliciting farmer cooperation in the program. As an initial step, several farmers with fair to good management practices were enlisted to work out the details of the farm management process. Specifics on the contents of the agreements were developed, along with details of a signature sheet. The signature sheet is signed by all parties to the agreement and each signature prefaced by a statement of intent.

As mentioned, each agreement follows closely the framework of the traditional farm plan, with the exception that consideration is given to improvement in water quality as well as soil and cropping improvements. A list of the information contained in a typical farm management agreement is presented below:

1. The conservation district cooperative agreement, which sets forth, in general terms, what the district will do or provide and what the farmer will do.
2. A map showing delineation of the soils within the entire farm unit.
3. A map showing field boundaries, land uses, access routes, headquarters, structural facilities (mechanical and electrical facilities used in the farming operation), and identification of all locations within each irrigation district unit of water delivery and return flow discharge point(s).
4. The soil description and interpretation upon which land use and treatment decisions will be made.
5. Tabulation of identified problems and existing soil and water management practices by irrigation unit.
6. Alternative vegetative, structural, or management practices specific to applicable cropping systems that will provide acceptable improvement of return flows.
7. Tabulation of decisions by farmer or by farm manager and SCS technician which relate to the above alternatives of specific identified practices (vegetative, managerial, or structural).
8. A statement to the effect that "Farm management agreements developed under this cooperative program are for the sole use of the landowner/operator, the conservation district, and DOE for the exclusive purpose of evaluating and implementing irrigation return flow improvements."
9. Review and approval by the appropriate conservation district as to knowledge and practicability of the farm management agreement and its contents.
10. A record showing contacts and supplemental data gathered during the planning and implementation period.

The above elements were included in a set of guidelines developed for the project staff. Originally, these were to be developed for the purposes of inclusion into regulations, since it was anticipated that the project would be expanded on a statewide level. This concept was premature, and the guidelines have remained as a working document only.

Following the first public meeting with the farmers of DID 5 and 18, a list of "significant contributors" was developed. This list was developed principally through the cooperation of the irrigation districts and was intended to focus attention on that minority of farmers who apparently had land and water management problems. Approximately 50 farmers were on this list.

The Operation Committee recognized that a significant problem existed on leased land. In some cases, farmers utilizing land owned by others were not concerned with the conservation of the soil resource or water quality. The problem of leased land had to be addressed. It was decided that attempts had to be made to identify the landowner and leasee. In some cases, this was possible through conservation district and irrigation district records, but in many cases the lessee could not be identified readily.

An early attempt was made by DOE regional personnel to contact some of the 50 farmers in person. The demand on time and manpower made this attempt infeasible. In addition, the level of cooperation achievable through sole DOE contact was questionable.

The Operations Committee decided that the most promising route to follow was to hold a meeting specifically for the 50 listed farmers. An invitation letter was mailed through the local conservation district calling for a meeting in late January 1976.

Response was good. There were 22 of the 50 who came to the session chaired by the South Yakima Conservation District (on behalf of the Operations Committee). The slide show was presented and remarks explaining the program were given by various members of the Operations Committee. Following a request by the Operations Committee, 100 percent of those attending requested farm evaluations. This was accomplished through distribution of request forms requiring a definite yes-no commitment.

A second similar meeting, preceded with invitational letters, was called the following month. Ten of the remaining 28 farmers appeared, and this session again resulted in 100 percent agreement to have their farm units evaluated. At this time, the point of diminishing returns had been reached and no further sessions were scheduled.

During these early sessions, it was recognized that there were probably some "falsely accused" on the list of 50. Following farm evaluation, this proved to be true and several of the 50 have been given assurances that they are utilizing good land and water management techniques.

Financial Programs

As an incentive to getting farmer involvement, the most readily available source of funding was explored — the USDA Agricultural Stabilization and Conservation Service program of cost sharing (ASCS). This program provides cost sharing for up to 50 percent of the cost of specified conservation practices. In this program, cost sharing can be provided through long-term agreements with ASCS for up to 10 years on any farm unit with a financial limitation of $25,000 (ASCS funds) on any particular farm.

Background and objectives of the Sulphur Creek Project were discussed with the Yakima and Benton County ASCS Committees. It was necessary to bring the Benton County ASCS Committee into the project because small portions of DID 5 and 18 lie in that county. These committees, made up of conservation district board members, direct the use of funds. Alternative proposed measures and possible costs to operators were explained to the committees. A special project was recommended for funding the eligible measures under the ASCS program. Under the suggested proposal, funds would be earmarked mainly for use in long-term agreements (LTA). It was felt that LTA would most ideally blend with the farm management agreement program.

The ASCS county committees and Sulphur Creek technical staff developed two special project applications for funding from the state ASCS funds. Again, it was necessary to have one located in Yakima County and one in Benton County. These proposals resulted in funding totaling $80,000 — $10,000 in Benton County and $70,000 in Yakima County.

The Yakima County committee set no priorities for LTA funds. Thus, the option for utilization of LTA as a long-range planning tool was nonexistent for Yakima County landowners. The Benton County committee did give farmers the option of LTA and several requests were received as a result.

ASCS cost-sharing requests resulted in the following planned improvements in Sulphur Creek area: (Because of the spinoff publicity from the activity in DID 5 and 18, other requests came in from the Sulphur Creek area in general; the following list represents those planned improvements in the total Sulphur Creek drainage.)

Number of Units	*Planned Improvements*
31	Piping open ditches for more efficient water control
12	Excess water management system improvements
32	Conversions from rill to sprinkler
2	Livestock storage and disposal systems
11	Desilting and debris basin tail water recovery systems

During the first year of operation, several resource conservations and development projects (RC & D) have evolved. RC & D funds are provided through the USDA, with the SCS providing the leadership in the program. Though the SCS provides leadership, RC & D projects are developed at a local level, with locally developed goals, and basically, locally run. RC & D projects differ from projects undertaken with ASCS funds in many ways, but primarily in the area of size. RC & D projects are community in nature and may help in supplying funds for such things as flood prevention, erosion and sediment control, agricultural water management, agricultural related pollution control, or fish, wildlife, and recreation development.

For example, in Sulphur Creek one application has been made to improve drainage outlets, and another is forthcoming on a group gravity delivery system to provide pressure delivery to about 700 acres. Pressure will be sufficient for sprinkler operation, doing away with numerous pumps.

Manpower seems to be the major constraint on the number of RC & D projects which are undertaken. It takes considerable effort to make all landowners aware of the program and to gain their cooperation in these types of projects. It is felt that if sufficient time were spent with the involved landowners in the Sulphur Creek area, there are a large number of RC & D projects which might be generated.

Project Outputs

Following the first year of operation of the Sulphur Creek Project, the following results have been obtained. In DID 5 and 18 and of the original 50 "problem" farm units, 5 agreements have been signed and another 22 are in the planning process. In the Sulphur Creek area, and outside of the significant 50, another 6 agreements have been signed and 9 are in the planning stage. Of the 50 farmers intensively contacted in DID 5 and 18, only 5 have shown some resistance to the Sulphur Creek approach.

During the 1977 irrigation season, it is anticipated that 23 plans will be signed in the Sulphur Creek area. Of these, 13 will come from that original list of 50 farmers. In addition, one-third (8) of these plans will cover farm units of over 1,000 acres.

Technical Problems and Economic Considerations

As mentioned, one of the first tasks of the technical staff as they entered the Sulphur Creek area was to develop some of the technical tools necessary for soil and water conservation planning. Along with conducting "mini" soil surveys of the area and gathering aerial photographs, the technical team set out to update what is commonly referred to as the "Technical Guide" for SCS planners. The Technical Guide sets out minimum conservation treatments required in specific situations to maintain the soil resource. The above, along with applicable portions of the SCS publication, "Irrigation Guide — Benton, Kittitas, Walla Walla and Yakima Counties"[1] (1974), were incorporated into a planner's handbook specific for Sulphur Creek.

As planning progressed during the first year of the project, it became apparent that some of the information had to be constantly updated, based on experiences specific to Sulphur Creek. For instance, the "Irrigation Guide" lists maximum criteria for irrigation including that for nonerosive streams, intake rates, row spacing by crop, peak and monthly consumptive use, maximum length of run (based on soil and slope), net moisture replacement (based on soil), and gross application (-based on slope and irrigation efficiency). In the

Sulphur Creek area, it was found that the "Irrigation Guide" contained some errors. Some soil intake rates, for instance, varied ten-fold from those in the Irrigation Guide. The effect of errors of this magnitude are apparent — low intake rates will affect length of run, initial stream size, erosive stream size, advance rates, irrigation time, etc. Consequently, new realistic intake rates had to be found to reflect the situation in Sulphur Creek.

Another significant problem found in the Sulphur Creek area was erosion in tail water systems. Many irrigators were found to be properly managing water at the head end of the fields. However, because in many cases 50-100 small flows would accumulate in collection ditches, erosive streams would be developed. This problem was solved on several units through piping collection ditches and utilization of dropped inlets. Dropped inlets are vertical pipes which intersect the main collection pipe and are generally spaced at about 50-60 foot intervals. Sediment was measured leaving one field of wheat and found to be reduced by eight-fold with this type of system. The first irrigation following tillage generally causes the largest sediment load to return systems. This can be reduced or, in many cases, eliminated through the removal of a few inches of soil around the dropped inlet pipes — thus creating small sediment basins.

During the first year of the Sulphur Creek Project, many of the solutions recommended to the irrigators were simple and relatively inexpensive. For instance, the dropped inlet collection system described above would cost approximately $1,500 for a 40-acre field, with dropped inlets spaced every 50 feet ($37.50 per acre). The cost of creating small sediment basins around the dropped inlets would also need to be added, but would be a minimal yearly cost, probably done by wheel tractor/blade or by hand labor.

This type of collection system coupled with a sediment basin and repump system would cost approximately $5,500 per 40-acre block (or $137.50 per acre). Conversion to sprinkler systems on a particular unit would average $250 to $800 per acre, depending upon the complexity of the system and the type of water delivery.

Any particular farm might require a combination of practices to reduce sediment losses. For example, a field that is currently well irrigated, utilizing a long run (1500 to 1700 feet) and has a sediment-loss problem, might need one or more of the following:

Items	*Cost Per Acre*
Splitting the run in half	$50 per acre
Tailwater collection system (dropped inlet)	$37.50 per acre
Sediment basin installation and maintenance	$12.50 per acre

The total cost for this particular unit would run approximately $100 per acre. Addition of a repump system to the sediment basin installation would raise the total capital investment to $225 per acre. When the costs of return flow clean-up under rill irrigation get this high, then sprinkler systems, with lower labor cost, begin to become more feasible.

Many farmers are already operating at a good management level. However, 5 to 10 percent are not, and the result has been a cost to their downstream neighbors and, of course, in terms of overall water quality in the basin. Taking the average cost between the two systems mentioned above ($100 with sediment basin and $225 with sediment basin and repump) — $160 per acre and projected over 10 percent (problem units) of the 247,000 acres of rill irrigated land in Yakima County (24,700 acres), it would yield a total projected cost of approximately $4 million to carry out these practices. This figure, of course, is an estimate not considering the size of those operations which seem to have a problem. It has been the experience in the Sulphur Creek area that those farming larger operations tend to have more of a problem. Additionally, annual operation and maintenance costs have not been considered.

It has been found that utilizing a rather simple evaluation process, the conservation planner can pinpoint problems on an irrigated unit and make meaningful recommendations to aid in clean-up of return flows. From an overall standpoint, and from the results of Sulphur Creek, most recommendations include one or more of the following: Improved water management, shortening furrow lengths, reducing steepness of slopes through leveling, contour ditching, grassed waterways, filter strips, sediment basins, repump systems, or sprinklers on steeper more erosive soils. It is felt that the Sulphur Creek evaluation procedure will yield the proper set of alternatives for a particular field. They allow the operator to make an informed and intelligent decision on how to get the most out of his farm without undue damage to the resource base.

SUMMARY

Spawned by futile efforts to apply the NPDES permit system to agriculture, the Sulphur Creek project has clearly pointed to alternatives as a result of its first year of operation. Attitude changes, due to information and education, local input and control, and realistic regulations, are the key elements to minimizing pollutant loadings from irrigated lands. Any number of alternate programs would be designed containing these elements.

The three controversial issues apparent in 1973 have not yet been resolved: 1) Who is to receive the NPDES permit (should there be a permit system at all)? 2) Do those entities have the responsibility and/or ability to control waste from irrigated lands? and 3) Does EPA have authority to exempt certain categories of dischargers from the permit system?

From the administrative and technical standpoints, many common problems have developed during the past year. Some of these problems and solutions include:

1. A clear definition as to who had authority, control, and responsibility of the project should have been developed early in the project. A good deal of confusion and futile effort can develop in any project when the above factors are not clearly given to a project leader. In Sulphur Creek, almost six months had elapsed before a clear assignment of authority, control, and responsibility was obtained.

2. Information, and more importantly, education, should be given a high priority. Individuals cannot be expected to change their manner of operation without being influenced by something. It is felt that negative incentives such as threat of penalties should be reserved for extreme abuses of land and water resources. In a project such as Sulphur Creek, it is felt that education should be emphasized as a mechanism to bring about change and funding committed to this objective. Only through education will the farming community as a whole recognize that the objectives of the improved soil and water management, improved crop production, and improved water quality are compatible.

3. More emphasis should be given to the current level of technology. That is, there is some question of the ability of administrative agencies to either predict the specific results of any massive change in management practices or predict the economic impact on the farming community. Is our technical knowledge at a level such that accurate predictions can be made as to the interrelationships between tillage practice, water management, crop rotations, and economics? Can these predictions be made for any area, let alone a relatively large area such as a river basin? Experience in Sulphur Creek has indicated that we have a lot to learn. Also, it tells us that any requirements applied to a hydrogeographic area will have to be rather specific and aimed only at those gross abusers of land and water resources. At that general level, accurate predictions as to water quality improvement cannot be made at this time. Only through intensive intergovernmental cooperation, combination of resources, research, and clearly defined agency goals will predictions of this nature ever by accurately made.

4. The objectives and scope of any program should be clearly defined and remain unaltered during the life of the project. In Sulphur Creek, the information program was initiated to bring out voluntary improvement in management practices. However, the objectives and scope of the project changed in its initial year, giving rise to some unresolvable problems. An example is that the general publicity given to the project as it was originally designed (headlines such as "Farmers Told by Ecology Engineer to Clean Up Water") provided improvement on lands outside the target area. However, when the USGS/DOE/WSU monitoring programs began, the objectives became research in nature (as opposed to general action program). Control areas for a research project were not not available due to this "spin-off activity." Additionally, detailed outputs for the project were never prepared (it was designed as a general action program). It seems, however, that the success or failure of Sulphur Creek from an administrative standpoint may be based on the number of

agreements completed, the number of farmer contacts, or a clear definition of a "significant contributor." Perhaps these should have been objectives from the beginning.

In spite of these problems, Sulphur Creek can be termed a success after one year of operation. Although not documented in detail, it is felt that the levels of concern and awareness of agriculturally related water quality problems has risen in the agricultural community. For a voluntary program, cooperation has been satisfactory. It is known that agricultural management practices are improving because of the program. However, the resulting level of improvement of water quality may not be known until the results of monitoring programs have been thoroughly analyzed. This analysis will necessarily include considerations of farm economics and weather during the monitoring period. Perhaps, a reliable correlation between the project and water quality may never be found. Probably the largest successes of the program have been the recognition of the value of local control and input into governmental programs and the significant accomplishments that can be made through the combination of objectives of various agencies and organizations toward a single goal — a realistic approach toward a quality environment.

The "208" Planning Effort for Irrigated Agriculture in the State of Washington

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ABSTRACT

The Department of Ecology is reponsible for developing a "208" Plan for irrigated agriculture in the State of Washington. It is anticipated that Best Management Practices (BMP) will be utilized by individuals to come into compliance with a state-wide regulatory program (possibly NPDES). Water quality committees formed through local conservation districts, with representatives from all interested groups, will develop BMP based on the following criteria: (1) economic feasibility; (2) local acceptability; and (3) water quality improvement.

INTRODUCTION

As directed by Section 208 of P.L. 92-500 and initial regulations, three urban drainage areas of Washington were designated as area-wide waste treatment planning areas. They are portions of King, Snohomish, and Clark counties. Comprehensive planning has been underway in these areas for some time.

Through Federal court direction (NRDC filed suit based on the urban-industrial limitation of initial regulations), DOE is active in "208" planning for those areas of the State not designated under initial regulations. Because of funding limitations, the Department of Ecology (DOE) has opted for a program which will emphasize "non-point" source problems in specific areas of the State. Hopefully, solutions to these problems developed during the "208" process can be extrapolated to other areas of the State having similar problems. The Federal courts have given states until November 1978 to complete their 208 planning.

The major elements of Washington's approach are as follows:

Problem	*Responsible Planning Entity*
Urban-industrial non-point sources	Designated areas
Irrigated-agricultural sources	DOE and State Conservation Commission
Dryland agricultural sources	State Conservation Commission
Dairy waste	State Conservation Commission
Groundwater disposal	DOE
Silviculture	DOE
Implementation assurances	Consultant

Irrigated Agriculture

Comments here will be restricted to the irrigated-agricultural element. The final product of the irrigated-agricultural element will be a result of local planning, not by agencies, but by local citizens. Basically, there will be two objectives: (1) to develop Best Management Practices (BMP) for on-farm management improvements and (2) to develop a program to address the NPDES regulations.

It is anticipated that following the "208" process, Best Management Practices (BMP) will be utilized by individuals to come into compliance with a state-wide regulatory program (possibly NPDES).

Major activity in the irrigated-agricultural element will occur at the local level. Conservation districts in irrigated areas are being urged to accept the responsibility for organization of the local input. At this time, it appears that water quality committees will be formed

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through the conservation districts with representation from all interested groups. The principal function of these water quality committees will be to develop a list of BMP. The criteria for judging any particular management practice will be three-fold:

1. It must be economically feasible.
2. It must be locally acceptable.
3. It must improve water quality.

Washington State Cooperative Extension Service, the SCS, the Conservation Commission's irrigated-agricultural specialists, and DOE personnel will aid these local groups in organizational and technical matters.

Basin-wide work groups will also be formed in each of the two major irrigated areas in Washington — the Yakima Basin and the Columbia Basin (Figure 1). These groups will have the principal function of assimilating information provided to them from the local committees. They will look for similarities in BMP from various areas and refine the developing list of BMP. Membership in this group will include representation from all of the local groups, irrigation districts, grower groups, and other interested entities.

Additionally, this group will have primary responsibility for development of a program to meet the objectives of existing NPDES regulations. Current regulations call for issuance of area-wide permits in 1978. Also, they provide for development of a State program which will meet or exceed the objectives of the proposed area-wide permits.

Permit proposals and refined lists of BMP will be passed on to a state-wide advisory committee for irrigated agriculture. This group has a similar but expanded membership from that of the former State Technical Advisory Committee for Water Quality Improvement. The tasks of this particular group will be to: (1) provide overall guidance to the process, (2) review permit proposals and BMP, and (3) guide the development of pilot projects, such as the one in Sulphur Creek.

The above process is not stepwise in nature, but rather is intended to be a dynamic interchange of ideas and information from the local to State level.

To assure local input from both major basins and from other irrigated areas, several additional items have been designed into the program. For instance: (1) creation of a large-scale information/education program, (2) an information dissemination and feedback system utilizing periodic newsletters, etc., (3) a series of workshops (1977) and hearings (1978) on the refined BMP list and NPDES proposals, respectively.

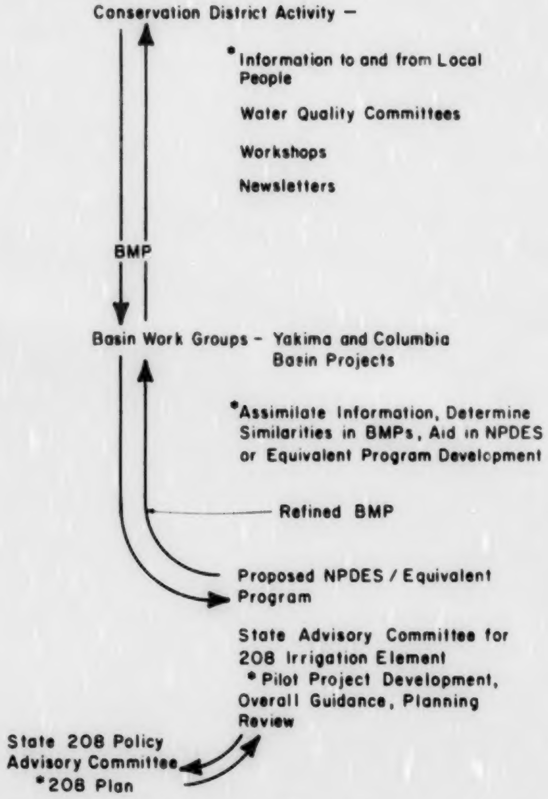
Conservation District Activity –
•Information to and from Local People
Water Quality Committees
Workshops
Newsletters
BMP
Basin Work Groups - Yakima and Columbia Basin Projects
•Assimilate Information, Determine Similarities in BMPs, Aid in NPDES or Equivalent Program Development
Refined BMP
Proposed NPDES / Equivalent Program
State Advisory Committee for 208 Irrigation Element
•Pilot Project Development, Overall Guidance, Planning Review
State 208 Policy Advisory Committee
•208 Plan

Figure 1. Washington's 208 planning process for irrigated agriculture.

Information from the Sulphur Creek project will be utilized in the 208 process to aid in the development of BMP and permit proposals. Because of the anticipated value of Sulphur Creek information, the project may be extended to November 1978, the proposed termination of the 208 process. Additionally, other pilot projects are under consideration currently and may be undertaken in the next irrigation season (1977).

In the Yakima Basin, long-range planning has concurrently been conducted by three federal agencies — the Bureau of Reclamation, the Corps of Engineers, and the Soil Conservation Service. The DOE has entered into an agreement with the three agencies for the purpose of avoiding duplication and providing a free exchange of information. Because of this agreement, outputs from the planning of these agencies will be incorporated, as appropriate, into the final Washington State 208 Plan. It should be noted that some interim outputs will have to be used, because planning by the Bureau of Reclamation and Corps of Engineers will continue far beyond November 1978 and on into 1980 and 1981.

The 1973 Agreement on Colorado River Salinity Between the United States and Mexico

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ABSTRACT

The background of the conflict between the United States and Mexico over the salinity of the Colorado River water delivered to Mexico, the early attempts to resolve the conflict, the meetings and negotiations that led to the latest agreements, a description of the agreement, the legislation that implements that agreement, and necessary future actions are presented.

In August 1973, the United States and Mexico executed the latest in a series of agreements that have attempted to settle the dispute between the two countries concerning the salinity of the Colorado River. The agreement is called the "Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River". In June 1974, the Colorado River Basin Salinity Control Act was enacted which authorized the construction of facilities considered necessary to implement the agreement and, in addition, authorized a major basinwide salinity control program. This paper discusses the background of the conflict between the United States and Mexico over the salinity of Colorado River water delivered to Mexico, the early attempts to resolve the conflict, the meetings and negotiations that led to the latest agreements, a description of the agreement, the legislation that implements the agreement, and necessary future actions.

Mexico's Use of Colorado River Water

The Colorado River is extremely important to northwestern Mexico. Colorado River water, supplemented by groundwater supplies, has irrigated between 425,000 to 500,000 acres in Mexicali and San Luis Valleys. For many years, the dominant crop was cotton. In 1959, 84% of the irrigated acreage was planted to cotton. In recent years, other crops have replaced cotton, as indicated by the following table:

IRRIGATED ACREAGE IN MEXICALI AND SAN LUIS VALLEYS IN ACRES

Crop	*1970*	*1975*
Wheat and Barley	172,140	151,764
Cotton	145,273	107,713
Miscellaneous	51,996	124,482
Alfalfa	36,452	46,393
Safflower	20,739	39,654
Total	426,600	470,006

The city of Mexicali, a city of about 400,000 people, obtains its basic supplies of 32,000 acre-feet a year from the Colorado River. Since 1972, the city of Tijuana, with a population of about 500,000 persons, has been receiving an average of 8,000 acre-feet a year of Colorado River water under a temporary agreement with several California agencies while an aqueduct was being planned and constructed. The aqueduct, scheduled for initial operation in late 1977, will enable Mexico to deliver 100,000 acre-feet a year of Colorado River water to Tijuana.

The Mexican Water Treaty

In February 1944, the United States and Mexico signed a treaty concerning utilization of the Colorado River as well as the Tijuana River and the Rio Grande. The most important provision of the treaty, with respect to the Colorado River, is the allotment to Mexico of a guaranteed annual quantity of 1.5 million acre-feet a

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year (maf/yr). The treaty was a result of years of negotiations and one of the contentious issues was salinity.

California made a major issue of water quality during the Senate hearings. The State Department defended the large allotment to Mexico by stating that up to 750,000 af/yr would come from irrigation return flows below Imperial Dam and would probably go to Mexico irrespective of any treaty. Senator Downey of California questioned the usability of the supply going to Mexico if the State Department estimates of return irrigation flows were correct. He made a remarkably accurate prediction in 1945 by stating that because of the ambiguity in the Treaty concerning water quality, Mexico would come back in 25 or 30 years and demand better quality water. State Department representatives, their consultants, and Senate supporters denied that there was any ambiguity in the Treaty. They stated that water quality was extensively discussed, and that Mexico fully understood that the Treaty required them to take irrigation return flows irrespective of the salinity of those return flows. In response to a question at the hearings before the Senate Foreign Relations Committee, the State Department consultant said the United States could deliver water to Mexico under the Treaty, as much as 500,000 to 750,000 af/yr, even if it would not have any value for irrigation purposes. The State Department pointed out that the specific provisions that were included in the Treaty to insure that Mexico must accept return flow and drainage water are in Articles 10 and 11. Article 10 states that Mexico's allotment included water from "any and all sources" and would be "for any purpose whatsoever". Article 11 states that "waters shall be made up of the waters of the said river whatever their origin".

In April, 1945, the Senate ratified the Treaty by a vote of 76 to 10. Of the 14 Basin state senators, only the two California senators and one Nevada senator voted against the Treaty.

In testimony before the Mexican Senate, the Mexican negotiators were telling a different story from that told by their United States counterparts. One of the Mexican negotiators said it was understood between the two countries that the water delivered to Mexico must be of good quality. He stated that Mexico could demand water similar in quality to that which she was currently using. Recognizing the difficulty of this demand, he said that Mexico would not object to receiving water similar to that used by the United States at Imperial Dam, the last diversion point in the United States. The Mexican Senate unanimously ratified the Treaty in September 1944.

Drainage from Arizona's Wellton-Mohawk Project

Between 1945 and 1961, there were no major problems with respect to the river, as the salinity of the water delivered to Mexico at the Northerly International Boundary was generally within 100 parts per million (ppm) of the water at Imperial Dam, the last major diversion for users in the United States. In 1961, the Wellton-Mohawk Irrigation and Drainage District in Southwestern Arizona commenced operation of a system of drainage wells which discharged saline water into the Colorado River below the last United States diversion, but above the Mexican diversion. The drainage water included a substantial proportion of highly saline groundwater that had been concentrated through reuse during the previous half-century. Initially, it had a salinity of around 6,000 ppm. As a sharp reduction in river flows to Mexico occurred at the same time, the combined impact of the Wellton-Mohawk drainage water and reduction of dilution water was a sharp increase in the salinity of the water delivered to Mexico, from an average of around 800 ppm in 1960 to plus 1500 ppm in 1962. Mexico raised strenuous objections to receiving the drainage waters.

Although, as previously indicated, the United States intended that Mexico must receive return flows below Imperial Dam under the Treaty, it had not been anticipated that there would be return flows as high in salinity as the Wellton-Mohawk drainage or that there would be such a precipitous rise in the salinity of the waters delivered to Mexico. Consequently, after the winter of 1961-62, the United States undertook certain provisional measures to minimize the impact of the high salinity drainage returns from Wellton-Mohawk. The United States also entered into negotiations with Mexico to arrive at a practical solution. The State Department asked each of the governors of the seven Colorado River Basin states to appoint two members to a reconstituted Committee of Fourteen in order to advise the State Department in connection with the salinity problem. The Director of the California Department of Water

Resources and myself are currently the two California members of the Committee.

In the past several years, approximately 500,000 af/yr of the 1,500,000 af/yr guaranteed to Mexico has come from drainage water below Imperial Dam. Of this amount, the Wellton-Mohawk Project contributes about 220,000 af.

Interim Salinity Agreements

Minute No. 218

Extensive negotiations were conducted between 1962 and 1965 and, in November 1965, a five-year agreement was incorporated in Minute No. 218. (The "Minute" form is a record of the International Boundary and Water Commission, United States and Mexico.) Under Minute No. 218, the United States undertook the following actions at a cost of $12 million:

(1) Constructed an extension of the Wellton-Mohawk Drain so that drainage water could either be bypassed around Morelos Dam (the Mexican Diversion Point) or mixed with other Colorado River waters above Morelos Dam, at the option of Mexico.

(2) Constructed additional drainage wells in the Wellton-Mohawk Project which allowed selective pumping of the most saline waters at times when Mexico would be bypassing Wellton-Mohawk drainage water, and allowed the pumping of higher quality groundwater at times when Mexico would be using Wellton-Mohawk water.

(3) Replaced a portion of the bypassed Wellton-Mohawk water which resulted in the release of approximately 40,000 acre-feet of mainstream water per year from Imperial Dam in excess of the 1.5 million acre-feet per year guaranteed by the Treaty.

Under the measures taken by the United States, the quality of the water delivered to Mexico was improved from average annual values of about 1500 ppm in 1962 to 1240 ppm in 1971. Minute No. 218 was entered into for a specific period and was to expire in November 1970. Accordingly, the United States and Mexico commenced negotiations with the purposes of arriving at another five-year agreement. However, Mexican officials did not want to enter into a new long-term agreement in November 1970, since a new administration was taking office in December 1970.

Negotiations commenced in 1971 with the new Echeverria administration. The United States, supported by the Committee of Fourteen, proposed a new Minute, which would have provided to Mexico, Colorado River water having the same salt concentration as would exist were the Wellton-Mohawk Project and all other projects in the United States below Imperial Dam in salt balance. This means that the tonnage of salt in drainage water originating from lands below Imperial Dam in the United States and delivered to Mexico would not exceed the tonnage of salt in the water applied to these lands.

Although the United States negotiators thought they were near agreement with Mexico in November 1971, Mexico finally rejected the United States' proposals and negotiations were discontinued, pending the results of a forthcoming meeting between Presidents Nixon and Echeverria. In the interim, the two countries agreed to continue operations under Minute No. 218.

Minute No. 241

On June 15 and 16, 1972, Presidents Nixon and Echeverria met and, following the meetings, issued a joint communique dated June 17, 1972. With respect to the Colorado River, President Echeverria gave the essence of the current Mexican position as wanting water under the 1944 Treaty to be the same quality as the water at Imperial Dam. President Nixon replied that "this was a highly complex problem and needed careful examination of all aspects". He said that the United States was prepared to:

> "(a) Undertake certain actions immediately to improve the quality of water going to Mexico;
> (b) designate a special representative to begin work immediately to find a permenent, definitive and just solution of the problem;
> (c) instruct the special representative to submit a report to him by the end of the year; and
> (d) submit this proposal, once it has the approval of this government, to President Echeverria for his consideration and approval."

The immediate action referred to by the President was formalized as Minute No. 241 of the International Boundary and Water Commission on July 14, 1972, and replaced Minute No. 218. This agreement was based on the salt balance concept previously advanced by the

United States and provided that the United States discharge 118,000 af/yr of Wellton-Mohawk drainage waters below Morelos Dam. The United States agreed to substitute for this water, on an interim basis, additional Colorado River water releases and waters pumped from wells on the Yuma Mesa. Thus, the total deliveries to Mexico would exceed the 1,500,000 af/yr guaranteed by the Treaty. Actions by the United States under Minute No. 241 included the discharge of 119,490 af of Wellton-Mohawk drainage water and the substitution by the United States on an equal amount of water during 1972-73. This resulted in reductions in the average annual salinity of waters made available to Mexico from 1242 ppm in 1971 to 1140 ppm for the year ending June 30, 1973.

Under the Minute, Mexico requested the United States to discharge the balance of the Wellton-Mohawk drainage waters (95,550 af), below Morelos Dam which was charged to Mexico's 1.5 maf/yr deliveries. As a result, the water diverted at Morelos Dam for the year ending June 30, 1973, had an average salinity of 980 ppm, which was about 130 ppm higher than the mean salinity of water arriving at Imperial Dam for the same period.

"Permanent and Definitive Solution" to International Salinity Problem

On August 16, 1972, President Nixon designated former Attorney General Herbert Brownell, Jr., as his special representative and gave him the task of finding a permanent solution to the Mexican salinity problem.

A federal task force consisting of policy and working level representatives from a number of the major departments of government, including Interior, State, Agriculture, Environmental Protection Agency and Office of Management and Budget, was formed to assist Mr. Brownell. The Task Force developed possible solutions, evaluated them and presented the results to Mr. Brownell. He also met with the Committee of Fourteen periodically to seek their advice on possible solutions. Mr. Brownell completed his report on time and submitted it to the President by December 31, 1972.

Several months after receipt of the Brownell report, President Nixon appointed Mr. Brownell as a special Ambassador and negotiations commenced between him and the Mexican representatives in the Spring of 1973. Ambassador Brownell continued to meet and discuss the negotiations with the Committee of Fourteen. Although the Committee supported the thrust of the proposed agreement with Mexico, they continued to state that the agreement would require certain actions on the part of the Federal Government in order to avoid damage to the basin states. The Committee of Fourteen was unable to receive firm assurances from responsible members of the government that actions satisfactory to the states would be taken.

Concerns of Basin States

On July 5, 1973, the Committee of Fourteen wrote Mr. Brownell, summarizing the issues previously raised in meetings that were still unresolved. Senators and congressmen from the seven basin states were also concerned that terms of the agreement could be detrimental to the water interests of the states. On July 20, 1973, all 14 senators and 36 congressmen from the seven basin states signed a letter to President Nixon, asking that final negotiations with Mexico not take place until there was substantial agreement on the issues raised by the basin states.

Ambassador Brownell met with the Committee of Fourteen on August 18, to discuss the issues that had been raised by the states, senators, and congressmen. Although agreement was not reached with the states on the outstanding issues, Brownell stated that he intended to try to reach an agreement with Mexico.

The actions requested by the basin states of the United States, and their eventual disposition, are summarized as follows:

1. *Federal government to assume responsibility for permanent replacement of the reject brine stream from desalting plant.*

The Administration responded by proposing that the replacement be conditional upon augmentation of the Colorado River by 2.5 maf/yr. The legislation supported by the states, and enacted as the Colorado River Basin Salinity Control Act, Public Law 93-320 (P.L. 93-320), declares it to be a national obligation and directs studies on feasible methods to provide replacement water are to be completed by June 30, 1980.

2. *Simultaneous authorization of features to implement the agreement with Mexico and the domestic Colorado River Basin Salinity Control Program.*

The Administration disagreed with this requested action and submitted legislation to

Congress dealing only with the Mexican agreement features. The States developed legislation incorporating both features, and these were enacted as Titles I and II of P.L. 93-320.

2. *Any agreement with Mexico to not impair or injure land owners in the United States.*

The Administration agreed to negotiate on this issue, and it was incorporated in P.L. 93-320, particularly with respect to land owners within the Wellton-Mohawk Irrigation and Drainage District.

4. *Federal government to continue research program to increase conversion efficiency of the Yuma Desalting Plant from 70 to 90 percent.*

The Administration apparently concluded that the need for such improved efficiency could be delayed for several years and, in addition, may be attainable through private industry research; however, the basin states have supported appropriation of funds to continue federal research on increasing efficiencies.

5. *Administration to proceed with development of Colorado River Basin water projects authorized by Congress, recognizing rights of the Basin states to develop their water resources.*

The Administration agreed to ease restrictions set by OMB on planning on water projects impacting on salinity of the Colorado River. This issue is complicated by other problems affecting federal funding of water projects.

6. *Federal government to obtain power needed for Yuma Desalting Plant from new sources so that power would not be withdrawn from existing uses.*

The Administration initially planned to obtain its power needs by recapture of capacity and energy through contract provisions of the Parker-Davis Project System. However, P.L. 93-320 negated this proposal by stating that sources of power for the desalting complex shall not diminish the supply of power to preference customers from the Federal power systems operated by the Secretary.

In addition to the issues as enumerated above, the States were concerned by Mexico's pumping of ground water along the Arizona-Mexico border which originates within the U.S. They urged that this issue be treated in any agreement with Mexico so as to protect and maintain the rights of the U.S. P.L. 93-320 included authorization of a well field in Arizona to balance the groundwater pumping by Mexico in the event the two countries are unable to reach an agreement limiting groundwater pumping.

Negotiations with Mexico

In his negotiations with Mexico, Mr. Brownell had to consider a number of conflicting views. The most significant are summarized below:

(a) The United States agencies represented on the federal task force had differing solutions to the problem. For example, the State Department desired a negotiated settlement in order to avoid further conflict with Mexico and the possibility of having to agree to a solution decided by a third party, such as the World Court. Also, there were a number of major outstanding problems with Mexico such as drugs, immigration, and economic policies that did not lend themselves to satisfactory solutions. The salinity problem was one that appeared to be capable of solution by expenditure of money. The Office of Management and Budget wanted a solution that did not involve expenditure of large sums of money.

(b) The seven basin states were anxious to work with the Federal Government to achieve a solution to this vexing problem. They did not object to deliveries by the United States of water in excess of 1,500,000 af/yr on a temporary basis in order to have a practical solution to the problem. However, the basin states opposed any permanent commitment to Mexico of water deliveries beyond that required by the Treaty.

(c) Mexico's basic position was that it was entitled to the same quality water as is delivered to Imperial Valley just across the border from Mexicali Valley. Mexican representatives also believed that they were entitled to substantial compensation for damages caused by saline Wellton-Mohawk waters since 1961.

Agreement with Mexico

After extensive negotiations, agreement was reached between Ambassador Brownell and Secretary of Foreign Relations of Mexico, Emilio O. Rabasa in the latter part of August and was approved by the two Presidents on August 30, 1973, and subsequently incorporated in Minute No. 242 of the International Boundary and Water Commission, which terminated Minute No. 241.

Minute No. 242 contains the following major provisions:

1. The United States shall adopt measures to assure that by no later than July 1, 1974, the waters delivered to Mexico upstream from Morelos Dam will have an average annual salinity of not more than 115 ppm, plus or minus 30 ppm, over the annual average salinity at Imperial Dam. This quality guarantee becomes effective upon authorization by Congress of the funds to construct the necessary works.

2. Until Congress authorizes the necessary works to provide the quality guarantee, the United States shall continue to bypass Wellton-Mohawk drainage water at the annual rate of 118,000 acre-feet per year and substitute therefore an equal volume of better quality water.

3. The United States will continue to deliver approximately 140,000 acre-feet to Mexico on the land boundary at San Luis, Mexico, with a salinity essentially the same as that of the waters customarily delivered there (approximately 1550 ppm).

4. The concrete-lined Wellton-Mohawk drain shall be extended approximately 53 miles to Santa Clara Slough (on the Gulf of California) with a capacity of 353 cubic feet per second. Construction and operation in Mexico would be performed by the Mexican Government, but at the expense of the United States.

5. Each country shall limit pumping of groundwaters in its territory within five miles of the Arizona-Sonora boundary near San Luis to 160,000 acre-feet annually.

6. The United States will support efforts by Mexico to obtain appropriate financing for improvement and rehabilitation in the Mexicali Valley. The United States will provide nonreimbursable assistance for those aspects of the rehabilitation program relating to the salinity problem, including tile drainage. The extent of this participation is to be negotiated in the future.

7. The new Minute is to be recognized as a permanent and definitive solution to the Colorado River salinity problem.

Analysis of "Permanent" Solution

Mexico receives major new benefits from the agreement. She receives a guaranteed quality at Morelos Dam related to the quality of water at Imperial Dam. All of the costs in money or water to achieve this quality guarantee is to be borne by the United States. Mexico has the promise of financial assistance with respect to salinity problems, including tile drainage in Mexicali Valley. In addition, the United States will support efforts by Mexico to obtain favorable financing for the improvement and rehabilitation of Mexicali Valley. Also at the United States expense, a concrete-lined canal is to be constructed in Mexico to discharge saline water.

The United States negotiators believe there are considerable tangible benefits to the United States. The agreement eliminates the possibility of long years of acrimonious controversy between the two countries. The agreement does not require any payments to Mexico for any past damages. Since the agreement is described as a permanent solution, presumably Mexico has waived any future rights to press for monetary damages. Mexico agreed to permanently accept 140,000 acre-feet per year of their treaty right at the Arizona-Sonora boundary. This is largely drainage water with a salinity considerably higher than that of the Colorado River. Although Mexico has accepted this water for years and utilized it, there was apparently no obligation on Mexico's part to accept the waters at this location until this agreement was signed. Although the United States will reduce the salinity of the Wellton-Mohawk drainage waters under the new agreement, Mexico has agreed that other drainage waters below Imperial Dam will continue to be accepted as part of the U.S. Treaty obligation. In summary, negotiators believe that the concessions made by the United States are in terms of money, not water. However, this is not entirely true, as the reject stream from the desalting plant currently estimated at 43,000 af/yr, will not be included as part of the 1,500,000 af annual obligation and will have to be replaced.

While the agreement is silent with regard to salinity control upstream of Imperial Dam, both the U.S. and Mexican negotiators agree that upstream salinity control is vital to the long-term success of the agreement. The Mexican government apparently believes that the United States has committed itself to a program to control the river's salinity upstream from Imperial Dam, for Foreign Minister Rabasa made the following statement to the press in Mexico City when the agreement was announced on August 30, 1973:

> ". . . the final result will be that the Mexicali farmers will have forever — they

> and their children and their children's children — water whose average annual salinity will never exceed 1010 ppm, which is perfectly acceptable."

When correction is made for the method of analysis for salinity used in Mexico, which is different than that used in the United States, and the 115 ppm differential between Imperial Dam and Morelos Dam is added, the 1010 ppm referred to above is equivalent to salinity at Imperial Dam at the time the agreement was signed.

Mr. Brownell has stated that unless the United States controls the salinity at Imperial Dam, in the future we will have a new salinity problem with Mexico.

Colorado River Basin Salinity Control Act

The Administration desired that the legislation to authorize the necessary works for implementation of Minute No. 242 cover just those works. The Colorado River Basin states and their Congressional representatives, however, considered that there is one Colorado River salinity problem and that any legislation should encompass both the Mexican salinity measures and a basin-wide salinity control program. Further, there were a few features relating to the Mexican salinity measures, such as replacement of the reject stream from a desalting plant, that the states consider to be an essential part of any legislation on the agreement with Mexico. Accordingly, two bills were introduced in Congress, the Administration's bill and one by the basin states, which latter bill included all the items deemed necessary to implement Minute No. 242, plus the items considered essential by the states implementing the Minute, and, in addition, a basinwide salinity control program.

Congress enacted the bill supported by the states and the Colorado River Basin Salinity Control Act, Public Law 93-320, became law on June 24, 1974. It consists of two parts, Title I — Programs Downstream From Imperial Dam, and Title II — Measures Upstream From Imperial Dam. The Title I measures consist of those features necessary to implement the agreement with Mexico, including some that are needed to protect the Colorado River Basin states. Title II directs the Secretary of Interior to implement a basinwide salinity control program. It includes authorization for construction of four salinity control projects and directs that planning reports be undertaken for twelve other projects.

Title I Features

Under Title I, the Secretary of the Interior is directed to proceed with a program of works to enable the United States to comply with its obligations under the agreement. Plate A shows the location of the major features of Title I. These authorized works and actions are:

1. A 129 million gallon per day desalting plant and the necessary appurtenant works to reduce the salinity of the Wellton-Mohawk drainage water.

2. A lined brine disposal channel to convey the brine from the desalting plant to Santa Clara Slough in Mexico.

3. Replacement of the first 49 miles of the Coachella Canal in California. This will reduce seepage losses by about 132,000 acre-feet a year, and the calculated water savings will be credited against stored water used by the government in complying with the agreement with Mexico. When deliveries to California are reduced in the future, the government will no longer be able to use the water salvage credits and, therefore, Coachella Valley County Water District will make annual payments on the canal replacement.

4. Various changes in the Wellton-Mohawk Irrigation and Drainage District in order to reduce the amount of annual drainage water from that District to 175,000 acre-feet or less. These changes would include a reduction in the lands irrigated from the authorized level of 75,000 acres to a level of about 65,000 acres, an improvement in irrigation efficiency, and other necessary activities.

5. Direction to obtain a source of energy for the desalting plant that does not diminish the supply of federal power for preference customers in the region.

6. A groundwater well field with a capacity of 160,000 acre-feet a year on the Yuma Mesa located within five miles of the Mexican border, and to acquire rights in lands overlying the groundwater areas to be pumped.

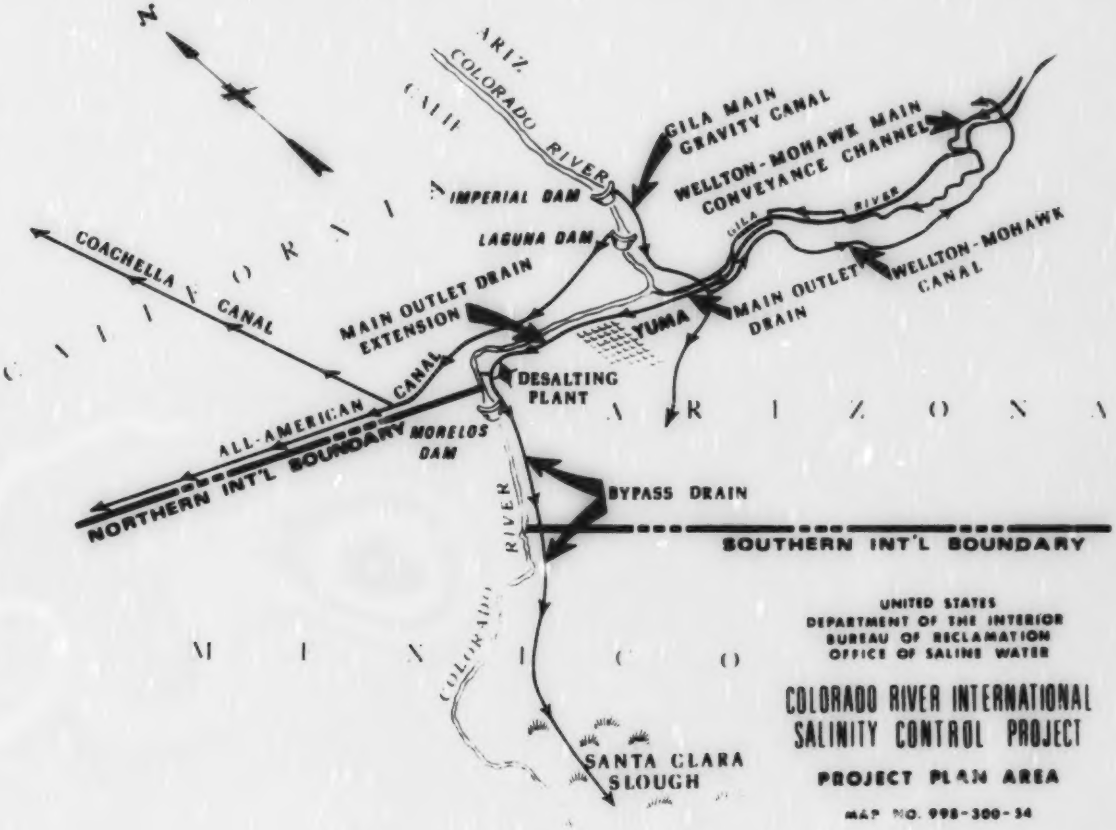
7. A study to be completed by June 30, 1980, of feasible measures for the replacement of the brine from the desalting plant.

The Congress authorized for appropriation the sum of $155.5 million for the construction of the preceding features, and, through fiscal year 1977, the Congress appropriated a total of $93.6 million to enable work in most phases to proceed rapidly. Extensive testing of the Wellton-Mohawk drainage water for problems to be overcome in desalting the water has been underway for over two years. This testing program has evaluated necessary pretreatment processes and costs, and has enabled possible desalting equipment and alternative desalting membrane combinations to be performance-tested in the actual field setting of the Yuma Desalting Plant. The Plant is scheduled to be completed by December 1981.

Funds have been made available to Mexico for it to construct the portion of the brine disposal channel within Mexico, and that work is now completed. A contract has been awarded for the construction of the United States section of the channel, and completion of the concrete lining is scheduled for March 1977, with the final work to be completed shortly thereafter. The 49-mile Coachella Canal reconstruction design is about completed, a form of contract for the repayment of allocated costs by the Coachella Valley County Water District is nearing final approval and the canal construction is scheduled for completion in March 1981.

Several thousand acres of land in the Wellton-Mohawk district have been acquired and retired from irrigation, and research is continuing on techniques and facilities to further reduce return flows from that district. The Bureau of Reclamation has performed preliminary studies of sources to replace the desalting plant brine, and has commenced an investigation of alternative sources. The border well pumping field is being acquired and pumping wells and appurtenant facilities laid out.

As this progress report shows, the United States is engaged in a major effort to observe its agreement with Mexico. Pending completion of the desalting works, the United States has been meeting the 115 ppm ± 30 ppm salinity differen-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ARIZ.
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COLORADO RIVER
GILA MAIN GRAVITY CANAL
WELLTON-MOHAWK MAIN CONVEYANCE CHANNEL
IMPERIAL DAM
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GILA RIVER
WELLTON-MOHAWK CANAL
CALIFORNIA
COACHELLA CANAL
MAIN OUTLET DRAIN EXTENSION
YUMA
MAIN OUTLET DRAIN
DESALTING PLANT
ARIZONA
ALL-AMERICAN CANAL
NORTHERN INT'L BOUNDARY
MORELOS DAM
BYPASS DRAIN
RIVER
SOUTHERN INT'L BOUNDARY
COLORADO
MEXICO
SANTA CLARA SLOUGH
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
OFFICE OF SALINE WATER
COLORADO RIVER INTERNATIONAL SALINITY CONTROL PROJECT
PROJECT PLAN AREA
MAP NO. 998-300-34

Plate A.

tial by discharging all Wellton-Mohawk drainage water below Morelos Dam without charge against the treaty and by substituting therefore Colorado River water from storage. The quantities bypassed were 111,000 acre-feet in the last half of 1974, 216,000 acre-feet in 1975, and 206,000 acre-feet in 1976. This stored water is to be replaced by the water salvaged by the Coachella Canal lining until such salvaged water is needed in California.

This program has effectively reduced the salinity of the water delivered to Mexico. In 1971, the last full year prior to the combined U.S.-Mexico programs to bypass Wellton-Mohawk drainage waters around Morelos Dam,

The costs of the facilities authorized by Congress has escalated sharply since 1974. The latest estimated cost of Title I facilities is $317,000,000, with a major portion of the increase due to the desalting plant and related facilities.

Future Actions

Although the title of the latest Colorado River agreement with Mexico (Minute No. 242) is "Permanent and Definitive Solution to the annual salinities were 1,160 ppm at Morelos Dam and 880 ppm at Imperial Dam, for a differential salinity of 280 ppm. Under the bypass program, annual salinities at Imperial and Morelos Dams were as follows:

ANNUAL SALINITIES, ppm

Year	*Imperial Dam*	*Morelos Dam*	*Differential*
1974	830	960	130
1975	830	960	130
1976	820	960	140

International Problem of the Salinity of the Colorado River", it is apparent that for the agreement to indeed become the hoped-for permanent solution, a number of actions now underway must be carried to completion. These actions include (a) construction of the world's largest desalting plant and appurtenant features, requiring appropriation and expenditure of hundreds of millions of dollars, (b) construction of the first 49-miles of the Coachella Canal, (c) continued development of the authorized Colorado River Basin salinity control program encompassing both natural and man-made sources of salinity in the entire Colorado River Basin, (d) appropriation and expenditure of over a hundred million dollars for the authorized salinity control units, (e) authorization, over the next several years, of additional feasible salinity control units and the subsequent construction of such units, and (f) better irrigation practices in both the United States and Mexico.

An Assessment of Irrigation Efficiencies and Drainage Return Flows from the Wellton-Mohawk Division of the Gila Project

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ABSTRACT

Public Law 93-320 authorized the construction of a large desalting plant to enable the United States to comply with its obligation under the agreement with Mexico of August 30, 1973 (Minute No. 242 of the International Boundary and Water Commission, United States and Mexico). The desalting plant will be constructed to treat the drainage waters from the Wellton-Mohawk Division of the Gila Project so these waters will be available for delivery to Mexico under the 1944 Mexican Water Treaty and Minute No. 242. By reducing the volume of drainage flows, the size of the desalting plant can be reduced. An interagency committee was established to determine and implement means of increasing irrigation efficiencies so as to reduce drainage return flows to the lowest practical volume and to identify an optimal economic solution relating desalting costs to specified irrigation efficiency levels. An assessment was made utilizing the water budget process to determine the relationship between increased irrigation efficiency levels and drainage return flows.

INTRODUCTION

Wellton-Mohawk Division of the Gila Project

The Reclamation Project, known as the Gila Project, was authorized and established under the provisions of the Reclamation Laws, the Act of June 16, 1933, and various appropriations acts for the purpose of reclaiming and irrigating lands in the State of Arizona. The Gila Reauthorization Act of July 30, 1947, provided for a reduction in the acreage and established the boundaries of the Gila Project, as shown on Figure 1. The Wellton-Mohawk Division was thereby authorized to include an area comprising approximately 75,000 irrigable acres of land, or such number of irrigable acres as can be adequately irrigated by the beneficial consumptive use of no more than 300,000 acre-feet of water diverted annually from the Colorado River. Wellton-Mohawk Division lands in southwest Arizona were reclaimed for agricultural purposes by importing Colorado River waters, beginning in 1952.

The Gila Gravity Main Canal delivers irrigation water to the Gila Project from Imperial Dam. The Wellton-Mohawk Check and Turnout located about 15 miles downstream from Imperial Dam diverts water to the Wellton-Mohawk Canal that serves the Wellton-Mohawk Division. The water delivery facilities in the Division include 108 miles of main canals and 227 miles of laterals and appurtenant structures. Three large pumping plants on the Wellton-Mohawk Canal lift the water a total of 170 feet. Small relift pumps are scattered throughout the Division on laterals.

The Wellton-Mohawk Irrigation and Drainage District (District) was formed in 1951 and in 1952 assumed the repayment obligation of the irrigation and drainage facilities. The Gila Project delivered the first Colorado River water to the Wellton-Mohawk Division in 1952 and the entire distribution system was in operation by the end of 1957. Care, operation, and maintenance of these facilities were assumed over a period of time by the District upon completion of construction.

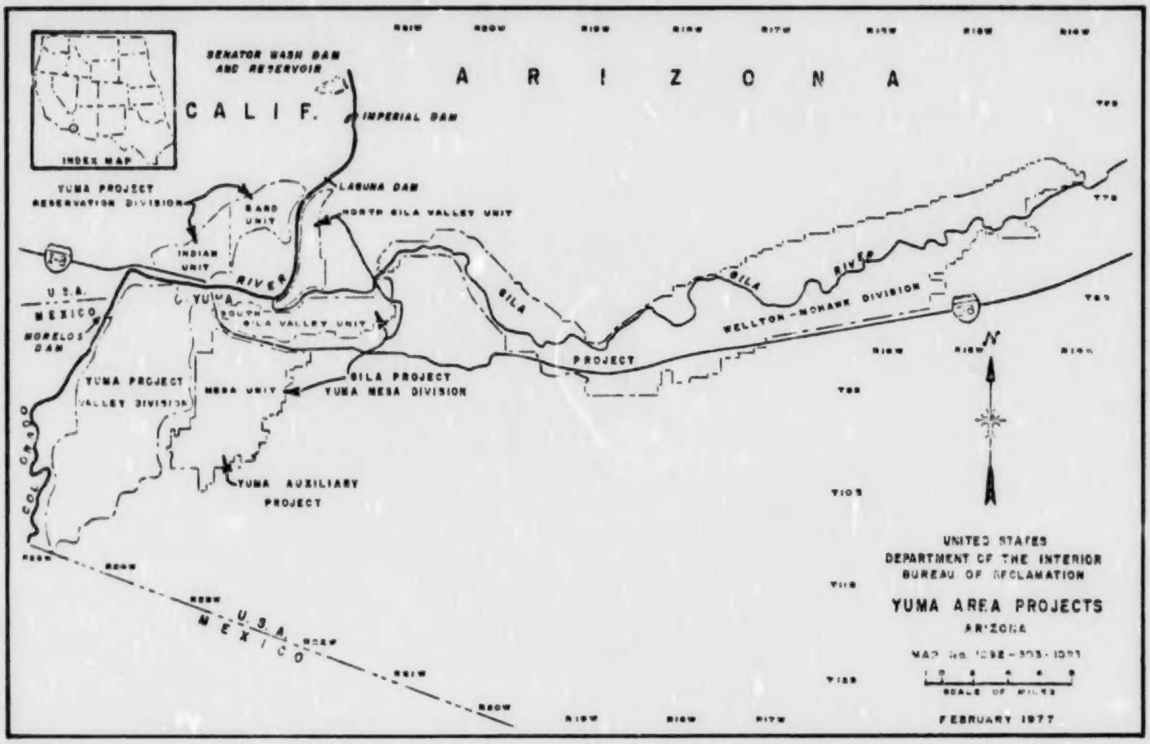
INDEX MAP
SENATOR WASH DAM AND RESERVOIR
CALIF.
ARIZONA
IMPERIAL DAM
LAGUNA DAM
YUMA PROJECT RESERVATION DIVISION
BARD UNIT
NORTH GILA VALLEY UNIT
INDIAN UNIT
RIVER
YUMA
SOUTH GILA VALLEY UNIT
U.S.A.
MEXICO
MORELOS DAM
GILA
GILA RIVER
WELLTON-MOHAWK DIVISION
PROJECT
GILA PROJECT YUMA MESA DIVISION
MESA UNIT
YUMA PROJECT VALLEY DIVISION
COLORADO
YUMA AUXILIARY PROJECT
U.S.A.
MEXICO
N
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YUMA AREA PROJECTS
ARIZONA
SCALE OF MILES
FEBRUARY 1977

Figure 1.

The Physical Setting

The District lands begin 8 miles east of the confluence of the Gila and Colorado Rivers in the vicinity of Yuma, Arizona. The Gila River floodplain throughout this reach is referred to as the Dome and Wellton-Mohawk Valleys, The adjacent southern Gila River terrace is known as the Wellton Mesa. Of the 75,000 irrigable acres in the District, 61,270 acres are valley lands and 13,730 acres are mesa lands. The area has a 12-month growing season with potential frost danger to tender crops between November 15 and February 15. Summers are dry and hot with maximum temperatures near 120°F. Minimum winter temperatures are about 25°F. Average annual rainfall is about 3.5 inches.

The bottom land soils have been formed from alluvial deposits of sands, silts, and clays. The soils are often stratified and platy and have had noticeable quantities of organic matter added through heavy vegetative growth. The arable soils have a relatively high water holding capacity because of the predominance of silt. Textures range from coarse sand to clay loam, but the most common textures are silt and silt loam.

The textures of the mesa soils are generally coarser than the valley soils, resulting in a lower moisture holding capacity. The soil textures range from sand to sandy loam, with a dominance of good quality loamy sands.

The Salinity Problem

After irrigation with water from the Colorado River was begun, the water table rose and by 1957 crops were threatened by drowning. Some old irrigation wells were reactivated for drainage wells, and others were constructed to remove excess ground water. This drainage water was originally discharged to the Gila River and was quite saline, initially averaging 6,000 ppm of total dissolved solids (TDS). From early 1960 through late 1961, the concrete lined Wellton-Mohawk Main Conveyance Channel (WMMCC) was constructed throughout the length of the District to carry drainage waters from 108 wells that were ultimately put into operation. The drainage water then emptied into the Gila River near its confluence with the Colorado and thence flowed to Morelos Dam where it was delivered to Mexico. In addition,

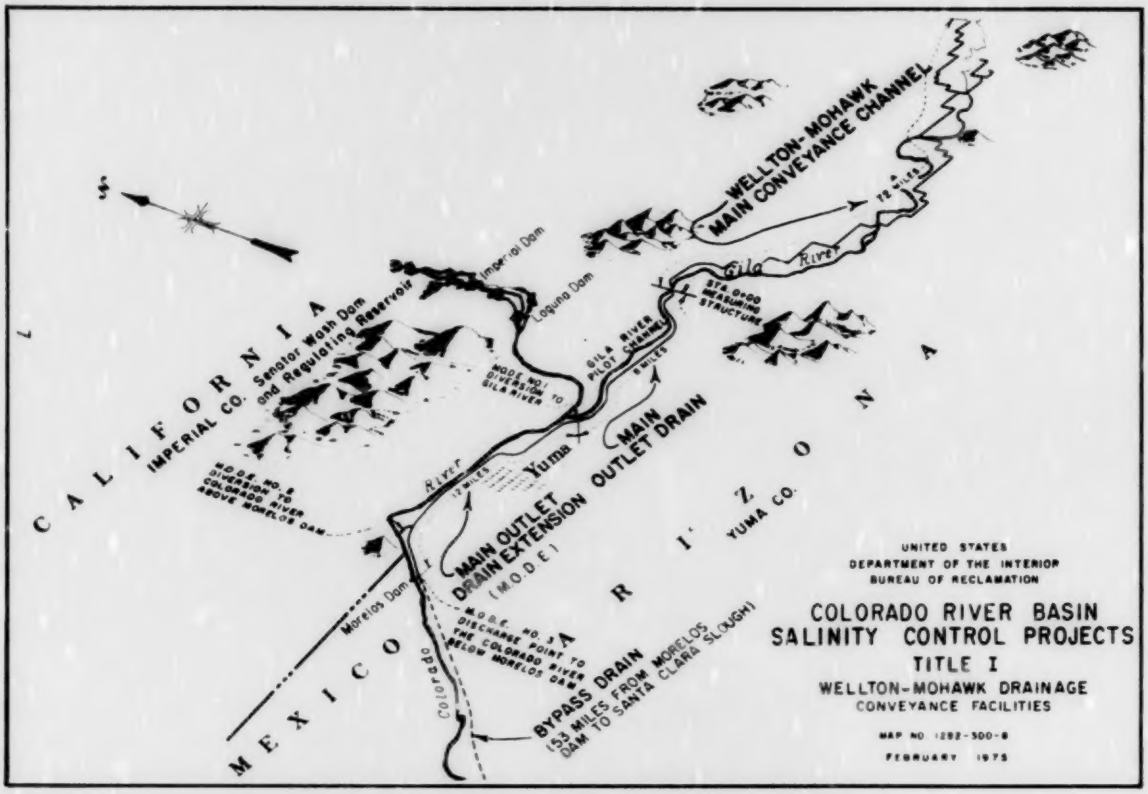
WELLTON-MOHAWK
MAIN CONVEYANCE CHANNEL
12 MILES
Gila River
Imperial Dam
Laguna Dam
STA. 0+00 MEASURING STRUCTURE
GILA RIVER PILOT CHANNEL
8 MILES
CALIFORNIA
IMPERIAL CO.
Senator Wash Dam and Regulating Reservoir
MODE NO. 1 DIVERSION TO GILA RIVER
MAIN OUTLET DRAIN
Yuma
12 MILES
River
M.O.D.E. NO. 2 DIVERSION TO COLORADO RIVER ABOVE MORELOS DAM
MAIN OUTLET DRAIN EXTENSION
(M.O.D.E.)
ARIZONA
YUMA CO.
Morelos Dam
M.O.D.E. NO. 3 DISCHARGE POINT TO THE COLORADO RIVER BELOW MORELOS DAM
MEXICO
Colorado
BYPASS DRAIN
(53 MILES FROM MORELOS DAM TO SANTA CLARA SLOUGH)
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER BASIN
SALINITY CONTROL PROJECTS
TITLE I
WELLTON-MOHAWK DRAINAGE
CONVEYANCE FACILITIES
MAP NO 1292-300-8
FEBRUARY 1975

Figure 2.

excess flows of the Colorado River which Mexico had received prior to 1961 came to a near end in that year. The excess flows had diluted the drainage water entering the river below Imperial Dam in previous years.

The combined effect of these developments increased the salinity of Colorado River water delivered to Mexico upstream of Morelos Dam from an annual average of about 800 ppm TDS to nearly 1,500 ppm TDS in 1962. The increase in salinity created an international situation and the President of the United States and the President of Mexico agreed in 1962 that it was urgent to find a mutually satisfactory solution.

In late 1965 the 12-mile long Main Outlet Drain Extension (MODE) was completed that allowed discharge of the Wellton-Mohawk Division drainage waters either upstream or downstream of Morelos Dam. A diagram of the Wellton-Mohawk drainage facilities, including the MODE are shown on Figure 2.

Operations of the Colorado River system in accordance with interim agreements with Mexico and coupled with improvement in the salinity of Wellton-Mohawk Division drainage waters reduced the average annual salinity of water made available to Mexico to about 1,140 ppm TDS for the year ending June 30, 1973. During this period Wellton-Mohawk Division drainage was in the range of 210,000 to 220,000 acre-feet per year. Some of the drainage was bypassed to the Colorado River below Morelos Dam and was not utilized by Mexico.

However, the United States and Mexico pursued a definitive, equitable and just solution to the problem of salinity of the water delivered to Mexico from the Colorado River.

Minute No. 242

Minute No. 242 of the International Boundary and Water Commission, United States and Mexico was approved by the two Governments on August 30, 1973. The Minute is entitled "Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River." Point 1 (a) of Minute No. 242 is as follows:

"1. Referring to the annual volume of Colorado River waters guaranteed to

Mexico under the Treaty of 1944, of 1,500,000 acre-feet (1,850,234,000 cubic meters):

(a) The United States shall adopt measures to assure that not earlier than January 1, 1974, and no latter than July 1, 1974, the approximately 1,360,000 acre-feet (1,677,545,000 cubic meters) delivered to Mexcio upstream of Morelos Dam, have an annual average salinity of no more than 115 ppm+ 30 ppm U.S. count (121 ppm + 30 ppm Mexican count) over the annual average salinity of Colorado River waters which arrive at Imperial Dam, with the understanding that any waters that may be delivered to Mexico under the Treaty of 1944 by means of the All-American Canal shall be considered as having been delivered upstream of Morelos Dam for the purpose of computing this salinity."

As Imperial Dam releases proceed downstream to Morelos Dam, they are influenced by return flows from irrigation projects which increase the salinity. The 115 ppm differential was negotiated with Mexico principally on the basis of excluding return flows of the Wellton-Mohawk Division of the Gila Project from the deliveries to Mexico and including other return flows to the river below Imperial Dam.

A large desalting plant has been authorized by the Congress for construction to treat the Wellton-Mohawk return flows, thereby reducing the salinity of the water delivered to Mexico upstream of Morelos Dam and preserving that quantity of the treated water for use in the United States.

An increase in irrigation efficiencies in the District will reduce desalting plant cost by reducing the quantity of water that will be treated. Reducing the quantity of water treated by the desalting plant will also decrease the quantity of water that will be lost as brine in the desalting process.

Public Law 93-320

Public Law 93-320 of June 24, 1974, authorizes construction, operation, and maintenance of certain works in the Colorado River Basin to control the salinity of water delivered to users in the United States and Mexico. The Act (88 Stat. 266) is cited as the "Colorado River Basin Salinity Control Act." Title I of the Act pertains to works authorized for construction downstream of Imperial Dam to meet the requirements of Minute No. 242, and among other things, provides for the following:

1. Construction of a desalting complex and appurtenant works.

2. Acceleration of the cooperative program of Irrigation Management Services with the District for the purpose of improving irrigation efficiency.

3. Reduction of approximately 10,000 acres in the authorized irrigable acreage in the District and further reduction in the irrigable acreage with the consent of the District as may be deemed appropriate.

4. Authorization, either in conjunction with or in lieu of land acquistion, to assist water users in the District in installing systems improvements, such as ditch lining, change in field layouts, automatic equipment, sprinkler systems and bubbler systems, as a means of increasing irrigation efficiencies; provided, that all costs associated with the improvements authorized and allocated to the water users on the basis of benefits received shall be reimbursed to the United States.

5. Authorization for amendment of the contract dated March 4, 1952, as amended, between the United States and the District to provide for reduction of the repayment obligation associated with the reduction of irrigable acreage in the District and for credit against the outstanding repayment obligation to offset any increase in operation and maintenance assessments per acre which may result from the District's decreased operation and maintenance base.

Advisory Committee on Irrigation Efficiency in the Wellton-Mohawk and Drainage District

Prior to proposing legislation to Congress [1] (concerning the United States requirements of fulfilling Minute No. 242) President Nixon, in mid-1973, directed that a working group be established to determine and implement means for increasing Wellton-Mohawk onfarm irrigation efficiencies.

The group includes representatives of the Department of the Interior, Environmental Protection Agency, Department of Agriculture, and the Office of Management and Budget. The group became known as the Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District. In August 1973, the Technical Field Committee (TFC) was created by the Advisory Committee for the following objective of assignment:

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[1] The proposed legislation eventually became Public Law 93-320.

> "The objective is to determine means of reducing the pumped drainage effluent from the District to the lowest practical volume through improvement of onfarm irrigation efficiencies and related measures. In addition, the TFC will identify an optimal economic solution relating desalting costs to specific efficiency levels."

The Advisory Committee also charged the TFC with specific tasks. A principal one was to determine the best estimate of the quantity and quality of Wellton-Mohawk return flows for use in design of the desalting plant. The task was to include (1) determining the measures required for attaining higher irrigation efficiencies or otherwise reducing the volume of drainage effluent from the District; (2) estimating ranges of costs and implementation times for attainable levels of onfarm and system irrigation efficiencies and estimating the volume and quality of the drainage effluent that would be associated with each cost, time, and efficiency level; (3) developing alternatives and recommending specific measures and a plan of implementation to achieve the stated objective; and (4) recommending a followthrough program for implementation, including the additional inputs or studies needed to refine or confirm irrigation efficiencies findings and conclusions.

The TFC consists of interagency members which include the Bureau of Reclamation, the Agricultural Research Service, the Soil Conservation Service, and the Environmental Protection Agency, with observers from the District and the U.S. Section, International Boundary and Water Commission.

THE ANALYSIS

Existing Practices

The analysis which associated onfarm measures with efficiency improvements was undertaken by the Technical Field Committee (TFC) utilizing cropping and water use data for calendar years 1970, 1971, and 1972.

The first step was an inventory and evaluation of the existing onfarm irrigation systems in the District. Soil surveys, aerial photographs, field investigations by the Soil Conservation Service (SCS), and records of the District and Natural Resource District[2] were used. All fields serviced by operating irrigation turnouts (about 1,200) were considered for the following data:

1. Lengths of lined and unlined farm ditches.
2. Field layouts including the length and width of borders and sizes of irrigation sets.
3. The slope and levelness of the fields
4. Size, type, and number of field turnouts.
5. Types of soil.

The inventory showed that over 47,000 acres had been developed into level basins and that about 633 miles of the 744 miles of onfarm ditches were concrete lined. In the leveled basins no tailwater occurs, and water in excess of consumptive use percolates to the groundwater table.

Of the approximately 65,000 acres in irrigation rotation in the District in 1973, about 31,000 acres of farm lands had been serviced by SCS and had adequate physical systems installed for efficient water management. Onfarm systems on the remaining acreage were analyzed to determine measures needed to improve irrigation efficiency and reduce deep percolation. Basic data collected on each field were used to determine present efficiencies and evaluated to determine (1) those fields where significant improvements are needed, and (2) what is needed to do a complete job of systems improvement.

Existing Assistance Programs

The Bureau of Reclamation and the District had established a cooperative IMS program in 1973. Under this program the farmer is provided information on when to irrigate and how much water to apply to replenish depleted soil moisture. The program involves determining the soil-water-plant relationship and uses various methods to determine the soil moisture status and the soil moisture depletion rate.

The SCS provides technical assistance through the Wellton-Mohawk Valley Natural Resource Conservation District. Information on irrigation management along with system improvement technical assistance is provided. Limited financial assistance is available.

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[2] The Wellton-Mohawk Valley Natural Resource Conservation District is the local organization of the Arizona State Land Department. It is responsible to fulfill requirements of the Arizona conservation laws. Assigned responsibilities includes restoration and conservation of land and other natural resources in Arizona.

Improvement Potential

Soil Conservation Service criteria which adapt the length and width of set to the soil intake rate and available water holding capacity were used to determine potential onfarm gravity system improvements. Further consideration was given to established irrigation practices in the District resulting in the following design assumptions:

1. Minimum practical length of run is 330 feet.
2. Depth of water application in a field would be a maximum of 6 inches.
3. Exactly 15 cfs would be available for each irrigation.
4. Fields are planted to close growing crops such as alfalfa.

Using these criteria, preliminary designs were developed except for the citrus acreage. The need for leveling was determined, as well as the most appropriate size of set. It was not believed practical to change the length of run or the grade on the citrus fields. Most of the fields in the District can be efficiently irrigated with 660-foot runs, although 400-foot runs were considered for some fields with coarse textured soils. Concrete lined ditches were included for all fields where they do not exist. Outlets and measuring devices were included as needed. Pressure system improvements for the citrus acreage were considered.

Citrus is located on the mesa where soils are coarse and highly permeable. Irrigation by flooding is not efficient on these soils and there is little prospect for improving irrigation efficiencies. Pressurized systems using tricklers or bubblers, however, were thought to be most promising and also offered advantages for fertilizer applications and savings in labor costs.

Many combinations and levels of assistance programs that could improve efficiencies were considered. They included improving gravity systems, use of new technology such as drip and bubblers on citrus and automation on both gravity and pressure systems, technical assistance and information service to design new systems, research and demonstration of new systems and how to apply the required irrigation application, and better measurement of water. Other factors that affect water use include economic benefits to farmers, cost sharing on assistance programs, water pricing policy, and a willingness on the farmer's part to improve his water management.

Program levels were developed to reflect (1) management and system improvements associated with various levels of irrigation efficiencies, and (2) a range of alternatives for selection of a recommended program.

Potential Irrigation Efficiencies and Costs

Four program levels and associated irrigation efficiencies were developed to evaluate and project reductions in return flows for 65,000 irrigable acres. A summary of the programs utilized to evaluate the potential for reducing return flows is presented in Table 1.

Program Level 1

Irrigation efficiencies for Program Level 1 were determined by reviewing the irrigation efficiencies for each crop for 1970, 1971, and 1972. With the knowledge gained in gathering the basic data and the evaluation of the existing onfarm systems capabilities, judgment was used to determine a probable increase in efficiencies that could be attained with effort placed on water management only. No physical improvements are included in Program Level 1 other than those available through ongoing Department of Agriculture programs. A research and demonstration effort with emphasis on water use management would be initiated with interested agencies. The IMS program in the District would be accelerated.

It was estimated that average onfarm irrigation efficiencies in the District would be increased from the average 1970 through 1972 level of 56 percent to 64 percent under Program Level 1 at an estimated total cost of $1,650,000 over 5 years.

Program Level 2

Program Level 2 includes IMS assistance and research and demonstrations, the same as for Program Level 1. In addition, a cost-share program would be implemented to improve onfarm systems with the lowest irrigation efficiency. Improvements on gravity sytems would be on a total of 11,000 acres. In addition, conversion to pressure systems on citrus would

TABLE 1

Summary of Programs to Reduce Return Flows
Wellton-Mohawk Irrigation and Drainage District
Price Base: 1973

	Improved Management		*Research and Demonstrations*	*Onfarm System Improvement*		*Total Installation Cost ($ Million)*	*Federal Installation Cost[1] ($ Million)*	*Annual Equivalent Federal Cost[1] ($ Million)*
Program Level	*IMS*	*Tech. Asst.*	*Total Cost*	*Gravity*	*Pressure*			
1 Farm Efficiency 64 percent	56,000 ac. 7 men $200,000/yr 5 years	2 men $50,000/yr 5 years	$400,000	Reorientation of ongoing program		1.65	1.65	.10
2 Farm Efficiency 69 percent	56,000 ac. 7 men $200,000/yr 5 years	5 men $150,000/yr 5 years	$400,000	11,000 ac. (in low efficiency group) ($2.45 M)	3,000 ac. drip & bubbler, 450 ac. sprinklers ($2.14 M)	6.74	5.53	.33
3 Farm Efficiency 72 percent	56,000 ac. 7 men $200,000/yr 5 years	6 men $200,000/yr 5 years	$400,000	20,000 ac. ($4.07 M)	450 ac. sprinklers 4,000 ac. drip & bubblers ($2.83 M)	9.30	7.51	.45
4 Farm Efficiency 82 percent	56,000 ac. 7 men $200,000/yr 5 years	8 men $250,000/yr 5 years	$400,000	30,000 ac. ($5.82 M)	8,000 ac. drip & bubblers 3,000 ac. sprinklers 14.50 ($6.03 M)	14.50	11.15	.67

NOTE: Annual equivalent private cost[2] including 25 percent cost sharing and operation, maintenance, and repair amount to: P.L. No. 1 - going; P.L. No. 2 - $325,000; P.L. No. 3 - $502,000; and P.L. No. 4 - $827,000.

[1] Based on 75 percent cost sharing for permanent onfarm irrigation improvement measures plus the value of program expenditures for technical assistance, IMS and R and D.

[2] Interest at 5-5/8 percent, 50-year project life.

be undertaken on 3,000 acres. The total cost of Program Level 2 was estimated to be $6,740,000 over 5 years. The total average onfarm irrigation efficiencies were not estimated but believed to be about midway between Program Levels 1 and 3.

Program Level 3

Program Level 3 includes total system improvements to gravity systems on 19,860 acres and pressure system installations on 4,000 acres of citrus in addition to IMS assistance and research and demonstrations. The total estimated cost of the program is $9,300,000 resulting in onfarm irrigation efficiencies of 72 percent.

Program Level 4

Program Level 4 includes total gravity system improvements on 29,600 acres and complete conversion to pressure systems on 8,000 acres which is all of the citrus acreage in the District. In addition, the IMS assistance and research and demonstrations would be included. The total estimated cost of the program is $14,500,000 and the average onfarm irrigation efficiency would be increased to 82 percent.

Program Level 4 efficiencies were based on the design efficiencies of the fields in the District assuming that all required improvements would be made. The design efficiency on flood irrigated fields would be 80 percent and pressure installations on the citrus acreage would operate at 85 percent. The overall average on farm irrigation efficiency would be 82 percent. It was determined that the potential for achieving Program Level 4 efficiencies was theoretically possible but beyond practical achievement on the entire District acreage in the foreseeable future.

Table 2 presents the irrigation efficiencies of the 1970, 1971, and 1972 average and for Program Levels 1 and 3. The District was divided into six segments according to topographical characteristics of the District and salinity characteristics of the aquifer to better evaluate the water and salt mixing taking place in the aquifer. There are five valley segments and one mesa segment.

Water Budgets

Accounting for water entering and leaving the aquifer underlying the District is the key to understanding relationships between onfarm irrigation efficiencies and drainage return flow. Water budgets were used to assess historical conditions, to predict future drainage returns, and are being used to assess the effects of the programs implemented to increase onfarm irrigation efficiencies. The water budget diagram depicted on Figure 3 illustrates the many components of water considered for balancing inflows and outflows with changes in storage.

The quantity and quality of drainge return flows from the District are influenced by (1) size of area irrigated, (2) crop distribution and related consumtive use, (3) onfarm irrigation

TABLE 2

Projected Irrigation Efficiencies for Program Level 1 and Program Level 3
Wellton-Mohawk Irrigation and Drainage District

	Irrigation Efficiencies			*Irrigation Efficiencies*			*Irrigation Efficiencies*			*Irrigation Efficiencies*		
Segment	*3 Yr. Avg.*[1]	*Program Level 1*	*3*[2]	*3 Yr. Avg.*[1]	*Program Level 1*	*3*[2]	*3 Yr. Avg.*[1]	*Program Level 1*	*3*[2]	*3 Yr. Avg.*[1]	*Program Level 1*	*3*[2]
	WHEAT			SORGHUM			ALFALFA			COTTON		
Dome	38	60	70	53	58	60	83	84	85	72	77	82
Roll	62	67	71	59	63	67	91	85	85	84	85	85
Tyson	77	82	85	76	79	81	82	83	85	98	85	85
Texas Hill	57	63	69	45	50	60	55	58	63	66	71	76
South Valley	59	66	70	52	57	62	71	76	82	70	73	76
Mesa	--	--	--	--	--	--	55	60	65	--	--	--
Wt. Avg. (Valley)	64	70	74	56	63	68	82	81	83	79	79	81
Wt. Avg. (Mesa)	--	--	--	--	--	--	55	60	65	--	--	--
	LETTUCE			MELONS			BURMUDA SEED			TREE FRUITS[3] [4]		
Dome	20	25	27	32	37	40	75	77	80	--	--	--
Roll	18	25	27	--	--	--	68	73	75	--	--	--
Tyson	21	25	27	--	--	--	71	74	76	--	40	65
Texas Hill	24	25	27	--	--	--	50	55	60	--	--	--
South Valley	20	25	27	--	--	--	57	62	66	--	--	--
Mesa	--	--	--	--	--	--	--	--	--	28	40	65
Wt. Avg. (Valley)	20	25	27	32	37	40	66	70	72	--	40	65
Wt. Avg. (Mesa)	--	--	--	--	--	--	--	--	--	28	40	65
	PASTURE (Includes Other Hay)			MISCELLANEOUS NOT HARVESTED (Less Citrus Not Harvested)								
Dome	39	44	51	34	39	41						
Roll	70	72	75	31	40	50						
Tyson	43	60	75	--	--	--						
Texas Hill	48	53	57	46	51	51						
South Valley	67	72	75	45	50	53						
Mesa	36	41	43	--	--	--						
Wt. Avg. (Valley)	60	64	70	41	44	49						
Wt. Avg. Mesa)	36	41	43	--	--	--						

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[1] Adjusted from District records. High irrigation efficiencies for alfalfa and cotton reflect contribution from ground-water.

[2] Includes pressure systems for orchards and limited sprinkler germination of vegetables.

[3] Includes grapefruit, lemons, limes, oranges, tangerines, and pecans.

[4] For computer run pecans in Tyson segment remain in miscellaneous at 65 percent irrigation efficiency.

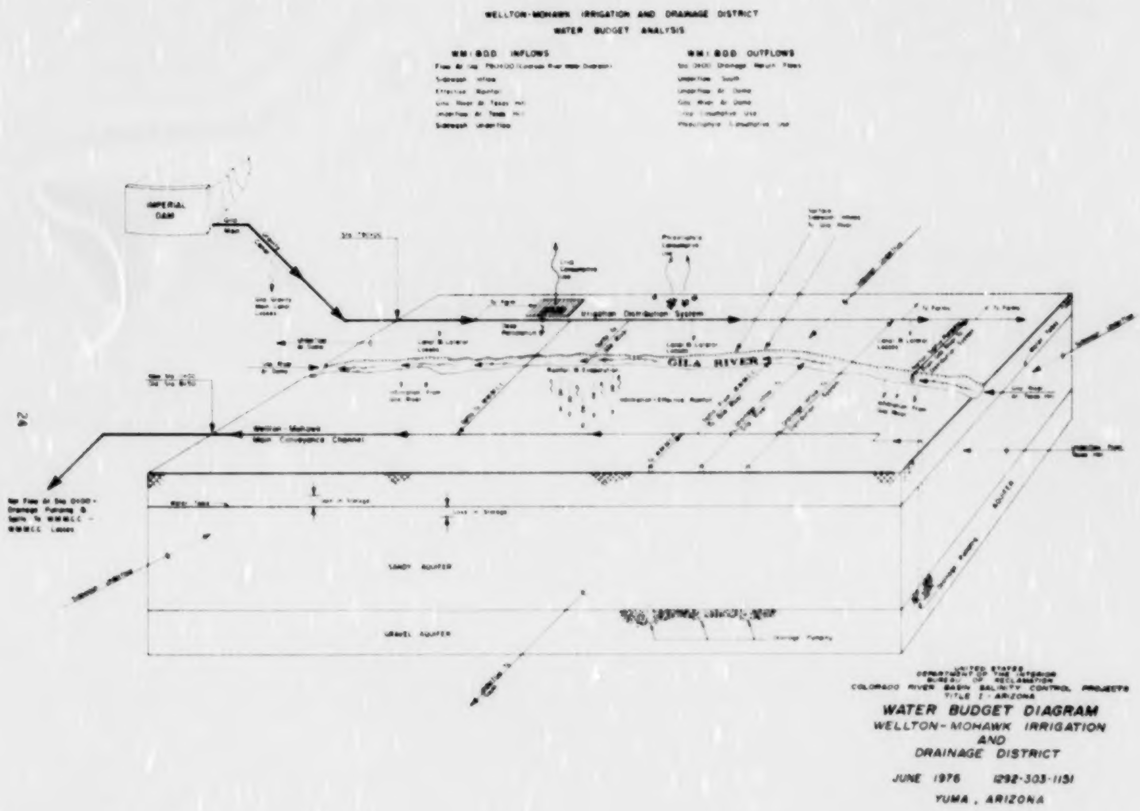
WELLTON-MOHAWK IRRIGATION AND DRAINAGE DISTRICT
WATER BUDGET ANALYSIS
WM I&DD INFLOWS
WM I&DD OUTFLOWS
IMPERIAL DAM
Irrigation Distribution System
GILA RIVER
Wellton-Mohawk Main Conveyance Channel
SANDY AQUIFER
GRAVEL AQUIFER
AQUIFER
24
UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION
COLORADO RIVER BASIN SALINITY CONTROL PROJECTS
TITLE I - ARIZONA
WATER BUDGET DIAGRAM
WELLTON-MOHAWK IRRIGATION AND DRAINAGE DISTRICT
JUNE 1976 1292-303-1151
YUMA, ARIZONA

Figure 3.

efficiencies, (4) distribution system operating efficiencies, (5) consumptive use by phreatophytes and other noncrop vegetation, (6) soil and drainage conditions, (7) aquifer recharge attributable to flooding, (8) rainfall, (9) salinity of the ground water, (10) salinity of the applied irrigation water, and (11) pumping operations.

Table 3 presents water budgets for the 1970, 1971, and 1972 base condition and for Program Levels 1 through 4. The closure on the water balance for 1970, 1971, and 1972 was in error by 31,000 acre-feet. This inbalance was believed to be related to many factors, such as (1) surface and subsurface inflow to the aquifer from side washes, (2) phyreathophyte use, (3) application of crop consumptive use values, (4) effective rainfall, and (5) subsurface outflow from the mesa to the south. The evaluation for the base year of 1970, 1971, and 1972 consistantly reflected the outflow to be greater than the inflow to the aquifer.

Because of the complexity of the many factors influencing the aquifer and the level of confidence that was placed on individual estimates, no attempt was made to force a balance on inflow versus outflow. It was believed more appropriate to project an inbalance along with the other components to determine pumping requirements when deep percolation is reduced by increasing irrigation efficiencies.[3]

Salinity Projections

The salinity of drainage returns was estimated by use of a digital simulation model. The model considers the more important chemical reactions such as solution or precipitation of lime and gypsum, ion exchange, interactions of calcium and bicarbonate ions with the partial pressure of carbon dioxide and ion pairing; other soluble salts are assumed to be in

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[3] Since 1973, adjustments and refinements have been made and the average inbalance has been reduced to about 5,400 acre-feet per year for the base years of 1970, 1971, and 1972.

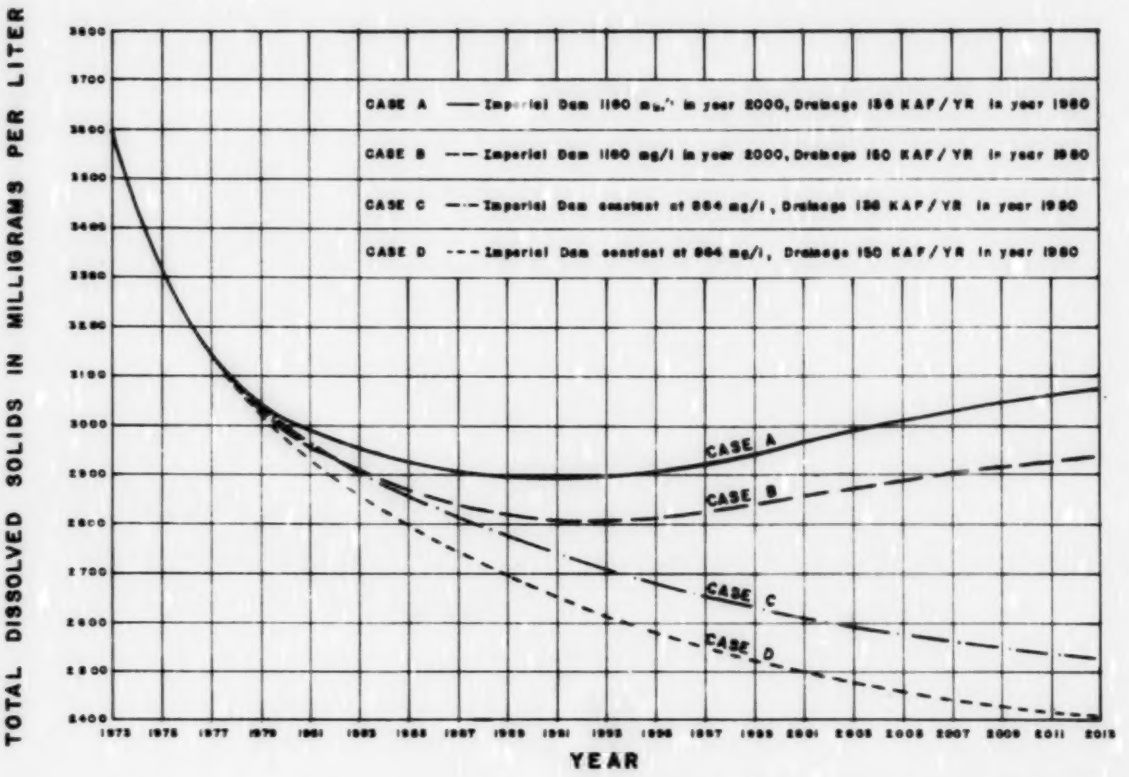
TABLE 3

Return Flows for 65,000 Irrigable Acres
Wellton-Mohawk Irrigation and Drainage District

			Improved Management	*Improved Management and Systems*		
		Water Budget for 1970, 1971, & 1972	*Efficiency of 64%*	*Efficiency of 69%*	*Efficiency of 72%*	*Efficiency of 82%*
			Level 1	*Level 2*	*Level 3*	*Level 4*
Input Data						
Irrigation Rotation	(Ac)	65,000	65,000	65,000	65,000	65,000
Irrigated	(Ac)	61,400	61,800 6/	61,800 6/	61,800 6/	61,800 6/
Crop Consumptive Use	(KAF)	252 1/	253 1/	253 1/	253 1/	253 1/
Irrigation Efficiency	(%)	56	64	69	72	82
Derived Data						
Delivered to Farms	(KAF)	447	395	367	351	309
District System Losses	(KAF)	51	51	51	51	51
Station 790, GGMC	(KAF)	498	446	418	402	360
GGMC Losses	(KAF)	16	13	13	12	11
Imperial Dam Diversion	(KAF)	514	459	431	414	371
Acquifer Inflow						
Deep Percolation	(KAF)	195	142	114	98	56
District System Losses	(KAF)	51	51	51	51	51
Texas Hill	(KAF)	2 2/	2	2	2	2
Effective Rainfall	(KAF)	11	11	11	11	11
Subtotal		259	206	178	162	120
Aquifer Outflow						
Underflow South	(KAF)	9	8 7/	3 7/	0 7/	0 7/
Gila River at Dome	(KAF)	4 3/	4	4	4	4
Phreatophyte Use	(KAF)	63 4/	58 8/	55	53	53
Subtotal		76	70	62	57	57
Flow at 8 + 30, WMMCC						
Inflow - Outflow	(KAF)	183	136	116	105	63
Adjustment	(KAF)	31	31	31	31	31
Estimated Return Flow	(KAF)	214 5/	167	147	136	94
Diversions - Returns	(KAF)	300	292	284	278	277

[1] Consumptive use on irrigated land estimated at 4.1 acre-feet per acre.
[2] Estimate of underflow into Wellton-Mohawk District.
[3] Includes surface flow and estimated underflow.
[4] Consumptive use of 3.9 acre-feet per acre on about 16,200 acres.
[5] Flows at 8 + 30, Wellton-Mohawk Main Conveyance Channel adjusted for estimated changes in aquifer storage.
[6] Assumes 95 percent of irrigable land under irrigation.
[7] Underflow south will decrease as irrigation efficiencies on the mesa improve.
[8] Phreatophyte use will decrease with increased capability to provide better drainage in critical areas.

the solution phase. Simultaneously, the model concentrates the input irrigation water in proportion to the consumptive use and percolates the water through the soil profile. The resultant deep percolation from the valley, mesa, and other areas was thus mixed and imputed to the aquifer system. The water and major ionic constituents were then routed through the aquifer by utilizing the principle of conservation of mass. The chemical reactions were presumed to occur in the upper 10 feet of the soil. Soil samples were withdrawn and analyzed from 80 borings to a depth of 10 feet made across each of the delineated segments. This provided the soil chemical and physical inputs. The chemistry of the water was determined from historical records. It is interesting to note that from 8 to 14 percent of the salts applied in the irrigation water are precipitated in the soil. The amount of the precipitation depends primarily



PREDICTED TREND OF WATER QUALITY
FOR WELLTON-MOHAWK RETURN FLOWS

Figure 4.

on the salinity of the input water, the partial pressure of carbon dioxide in the soil, and the irrigation efficiency.

Figure 4 shows return flows of 136,000 and 150,000 acre-feet with associated salinities projected for future conditions. The water quality of the return flows and the salinity of the aquifer are influenced primarily by quality and quantity of water applied for irrigation, crop and other vegetative consumptive use, chemical reactions within the system, and distribution system losses. Other inflows to the aquifer are believed to be of minor significance. During the initial operation of the pump drainage system, average annual salinity of the drainage was about 6,000 ppm total dissolved solids (TDS). As a result of aquifer freshening due to irrigation with Colorado River water and pump drainage operations, there has been a gradual improvement. The average annual salinity of the drainage was about 3,700 ppm TDS in 1973, which is about 100 ppm TDS higher than shown in Figure 4. However, the long-term change in the aquifer salinity should be approximately as shown provided that other conditions affecting the aquifer do not change significantly. Any assessment of the impact of changing irrigation efficiencies on the quality of the return flows must consider changes occurring in the aquifer.

A salinity of 3,000 ppm TDS is projected for 1980 with 136,000 acre-feet of return flow and about 2,490 ppm TDS is projected for about 2025 when the aquifer is in salt balance, assuming the salinity of Colorado River water stabilizes at about its present level. If no salinity controls are implemented above Imperial Dam, the salinity of the Colorado River is projected to increase to 930 ppm TDS in 1980 and to about 1,160 ppm TDS by 2000 [4]; under these conditions, the estimated salinities of the return flow would be about 3,020 ppm TDS in 1980 and about 3,230 ppm TDS in about 2025 when the aquifer is in salt balance.

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[4] Based on estimates included in "Status Report, Colorado River Water Quality Improvement Program," U.S. Department of the Interior, Bureau of Reclamation, January 1974.

For 150,000 acre-feet of return flow, the salinity of the aquifer is projected to be about 2,970 ppm TDS in 1980 and about 2,390 ppm TDS in about 2025 at salt balance, assuming no increase in the salinity of Colorado River water. For corresponding time periods and assuming an increase in salinity of Colorado River water, as previously discussed, the projected salinities are 2,990 ppm TDS and 3,050 ppm TDS, respectively. These projections take into account estimated precipitation of harmless salts in the soil profile as irrigation efficiencies increase, but do not account for possible infiltration from Gila River floodflows.

Acreage Reduction

Coupled with the proposal to construct facilities to treat Wellton-Mohawk return flows to meet requirements of Minute No. 242 is the provision to hold irrigated acreage in the District to near the present level. This will preclude increasing return flow from additional development. Authorizing legislation (Public Law 93-320) provides for reducing authorized irrigable acreage in the District from 75,000 to 65,000 acres and provides for further acreage reduction with the consent of the Wellton-Mohawk Irrigation and Drainage District.

Another consideration in acreage reduction is the District's allocation of Colorado River water under the Gila Reauthorization Act as previously discussed. Water budget analyses reflect that about 65,000 acres of land in irrigation rotation can be irrigated with the District's allocation of Colorado River water based on the definition of consumptive use contained in the Supreme Court Decree (Arizona vs. California) and the cropping pattern that prevailed in 1970, 1971, and 1972.

Irrigation Efficiency Improvement Impacts

A parametric study of desalting costs was undertaken to evaluate the relationship between desalting costs and volumes of return flow. In the study, the total range of probable desalting costs was explored. Design level parameters, such as plant recovery rates, TDS, and ionic water composition changes were examined over a broad range of drain flows to determine general cost sensitivities. Desalting cost variability to select levels of irrigation efficiency, river salinity levels, and long-term aquifer changes was also examined. The significant results of the cost study are presented in the following tabulation:

TABLE 4

Desalting costs for selected program levels

			Federal Cost	
Level	*Efficiency*	*Return Flow*	*Capital*[1]	*Annual Equivalent*[2]
	(Percent)	(1,000 AF/Year)	($\$X10^6$)	($\$X10^6$)
1	64	167	91.1	14.5
2	69	147	94.2	13.1
3	72	136	80.9	12.4

[1] For a representative, reverse osmosis membrane desalting process based on 1973 prices.

[2] Includes interest at 5-5/8 percent for 50 years on installation cost and all operation, maintenance, replacement, and power costs.

Cost Sharing for Onfarm Systems Improvements

The successful implementation of an onfarm program to provide high offsite benefits requires cost sharing incentives together with technical assistance to assure proper installation. The extent of cost sharing required involved three basic considerations:

1. The Federal benefits versus the owner benefits from the improvements.
2. The ability of the farmer to pay for the required improvements.
3. The short time period to install the required improvements and realize the associated reduction in return flows.

Crop budgets were used to evaluate economic incentives to farmers and to determine the benefits farmers would receive from implementation of an onfarm improvement program. The crop budget analysis included determination of gross returns from an average type and size farm operation in the District for various management levels. Production costs were subtracted from the gross returns to obtain net returns. It was assumed that installation of structural measures would raise management levels, resulting in increased net returns as benefits accruing to the farmer. Composite or average farms in the valley area and on the adjacent mesa were used to construct a net return per acre for each management level across the entire project area. The incremental increase in net returns that the average farmer would realize by moving from a low management level, or a medium management level, to a high management level were applied to the acres in each category to be served by the program to obtain the total increase in net farm returns.

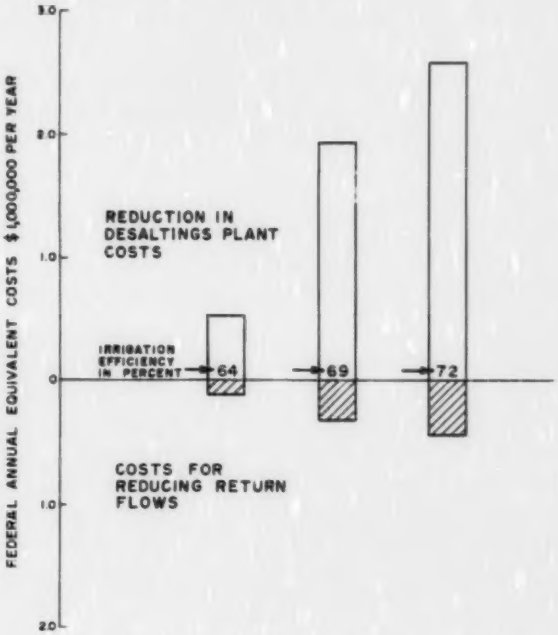
Federal benefits are the savings in desalting costs. Incremental drainage reductions were computed for each management level and multiplied by the incremental desalting plant savings per acre-foot to obtain desalting cost savings in terms of acres. These figures were then multiplied by the acres to be served to obtain the total Federal benefits. The procedure utilized indicated that the ratio of farmer benefits to total benefits would be about 30 percent. The crop budget process also indicated that the increase in net income would be sufficient to assist the farmer in paying for his share of the improvements.

Several cost sharing arrangements were considered for implementing the program. It was determined that procedures similar to those used previously by the Department of Agriculture to solve problems associated with high offsite benefits should be utilized. The contract concept involving a conservation plan developed with the farmer and an agreement between the farmer and the Federal Government to carry out the program over a period of years appeared the most appropriate. It was also believed that a successful program would require 70 to 75 percent Federal cost sharing to assure results on a timely basis. Program Level 3 appeared attainable with agressive management improvement, technical assistance, research and demonstrations, and an intensive education program.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It was concluded by the Advisory Committee that the highest level of irrigation efficiency capable of achievement prior to the desalting plant startup was a desirable goal. This was identified as Program Level 3 and has a cost-effective ratio of 6:1. Program Level 4, although projected as effective in reducing desalting cost was believed not practical of achievement in the time period required. The calculated return flow for Program Level 3 of 136,000 acre-feet per year is the objective. Irrigation efficiencies of 64 percent on the mesa lands and 74 percent on the valley lands are projected. The average District wide irrigation efficiency is 72 percent. The incremental reduction in desalting costs compared to the estimated costs of measures to reduce return flows are shown in Figure 5.



COST COMPARISON

INCREMENTAL REDUCTION IN DESALTING PLANT COSTS COMPARED TO COSTS FOR REDUCING RETURN FLOWS

Figure 5.

If the measures under Program Level 3 are fully implemented and if the effectiveness of these improvements increase irrigation efficiencies as projected in these studies, return flows should eventually reduce to 136,000 acre-feet per year. However, there are uncertainties in reaching this objective. They are (1) imprecision in the calculations of return flow quantities, (2) reservations that not all projected onfarm improvements will be fully implemented prior to the plant startup date or that the measures will be as effective in increasing irrigation efficiencies as estimated, and (3) changes in cropping patterns. The Advisory Committee was highly confident that return flows due to drainage requirements would be reduced to 175,000 acre-feet per year and considered it reasonable to expect that return flows would be reduced to 150,000 acre-feet per year by the early 1980's.

It was further concluded that the irrigable acreage in the District should be reduced by approximately 10,000 acres to preclude additional development that might increase drainage return flows and to insure that water use does not exceed the District's Colorado River allocation.

Recommendations

The Advisory Committee in its Special Report[5] made the following recommendations:

1. Acreage Reduction. The irrigable acreage in the District should be reduced from the authorized 75,000 acres by approximately 10,000 acres at an estimated cost of $9.5 million. This is in accordance with provisions of Public Law 93-320.

2. Program Level 3. It is recommended that Program Level 3, which includes the following items, be implemented:

a. Onfarm Measures. Install onfarm structural features to improve gravity irrigation systems on 19,800 acres, convert to pressure systems on about 4,000 acres of mesa land for use on citrus. Continued limited use of portable sprinkler pressure systems to germinate lettuce is anticipated. Apply a cost sharing of 75 percent Federal participation and 25 percent land owner participation to all onfarm structural measures, except portable sprinkler systems. Consideration should be given to continuing similar cost sharing arrangements after the desalting plant startup date to take advantage of opportunities that may exist to further reduce return flows.

b. *Improved Management.* Expand the IMS program to include insofar as practicable most of the irrigated acreage in the District.

c. *Technical Assistance.* Provide assistance by the SCS through cooperation with the Wellton-Mohawk Natural Resource Conservation District to achieve implementation of Program Level 3.

d. *Research and Demonstration.* Conduct research and demonstrations to evaluate and demonstrate measures to increase irrigation efficiency.

e. *Education and Information.* Develop and conduct programs to disseminate information to the water users so that they can utilize the improved systems and the technical and management assistance provided under Program Level 3.

f. *Cost.* The Federal share of the cost of Program Level 3 was estimated to be $7.5 million.

3. Distribution System Improvements. Deficiencies in the District distribution system that limit attaining higher irrigation efficiencies should be corrected and means found for financing required improvements.

4. Water Pricing Policy. The District should review the rate structure annually and set a rate for supplemental water sufficiently high to act as a deterrant against over-applications of irrigation water.

5. Operation and Maintenance of the Irrigation System. The District should improve its quality of operation and maintenance to the highest practical level for the efficient distribution and accurate accounting of water.

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[5] Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District. September 1974. Special Report. Measures for Reducing Flows from the Wellton-Mohawk Irrigation and Drainage District. U.S. Bureau of Reclamation.

Wellton-Mohawk On-Farm Systems Improvement Program

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ABSTRACT

The objective of the SCS in the Wellton-Mohawk Irrigation Improvement Program is to increase irrigation efficiency on farms in the district and thereby reduce return flows from the district. To accomplish this, the SCS enters into contracts with eligible landowners and operators to implement conservation practices that will further the program goals. Cost sharing is provided on a 75% federal, 25% cooperator basis.

Authority for U.S. Department of Agriculture and Soil Conservation Service participation in the Wellton-Mohawk Irrigation Improvement Program (Wellton-Mohawk On-Farm Systems Improvement Program) is contained in Title I of Public Law 93-320, the Memorandum of Understanding between the Departments of Interior and Agriculture, and the Memorandum of Agreement between the Bureau of Reclamation and the Soil Conservation Service.

The objectives of the program are to increase irrigation efficiency on farms in the Wellton-Mohawk Irrigation and Drainage District and reduce return flows from the District.

The Soil Conservation Service enters into contracts with eligible landowners and operators (cooperators) to install conservation practices that will directly contribute to the objectives of the program.

A cost-share rate of 75 percent Federal and 25 percent cooperator was established by the Secretary of Interior. Funds to cover the costs of contracts and technical services are transferred from the Bureau of Reclamation to the Soil Conservation Service under the Memorandum of Agreement.

Lands eligible for the program must be irrigated farmland within the Wellton-Mohawk District. Land being considered for purchase by the Bureau of Reclamation under the acreage reduction program is excluded.

A priority system for assisting applicants under the program was established by the Soil Conservation Service. Those lands with low efficiency are high priority.

As of January 1, 1977, ninety-four of the one hundred sixteen applications were on a high priority list.

Irrigation efficiency in the district averaged 56 percent during the three-year period 1970 through 1972 (33 percent on the sandy mesa lands and 65 percent on the fine-textured valley lands). The goal of the program is to raise the average efficiency in the District to 72 percent. (1)

Implementation of the program requires input from several disciplines. The soil scientist surveys the soils, and prepares a detailed soil map. The soil conservationist develops treatment alternatives and assists the cooperator select those alternatives that will contribute to program objectives. The engineer designs the structural practices and checks for compliance with contract specifications. Technicians make planning and design surveys and inspect construction. All staff members assist farmers with irrigation water management. Practices are installed by private contractors.

The contract specifies the practices to be installed and the timing of the installation. The contract extends two years beyond the year in which the last cost-shared practice is installed. This is to permit application of a water management system and to evaluate the results in terms of program objectives.

The design delivery of water from the irrigation district lateral to the farm headgate is fifteen cubic feet per second (c.f.s.). Two types of farm irrigation systems are being installed; flood and pressure pipeline. All the flood systems designed to date provide for applying the entire head of available water to a single level border. The borders are sized to enable a minimum 3-inch water application to be made. So far in our experience, the border sizes have varied from 2 1/2 to 20 acres depending upon the soil characteristics.

An integral part of the flood system is the water measuring device. During an irrigation it is important that the irrigator readily be able to determine the volume of water so that he may make adjustments in time of application. The irrigator has available to him a "farm irrigation guide" from which he can determine the time needed to apply a specific amount of water on each border.

A trapezoidal type critical flow depth flume developed by the Agricultural Research Service is the measuring device that was selected for use in the program. A staff gauge installed on the side of the flume can be read by the irrigator to readily determine water volume.

Water is delivered to the borders either through ports or turnout structures. Typical ports are 16-inch concrete pipe with a slide gate inlet. Three ports will normally handle a 15 c.f.s. head of water.

Where feasible, the entire head of water is delivered to a border through a single large turnout structure. Water delivery is regulated through a 46-inch wide jackgate. The structure is flared from the gate to a width of 15 to 20 feet. The field edge of the structure is usually beyond the ditch berm and poses no obstacle to farming operations.

Two types of pressure pipeline systems that qualify for the program are sprinkler and drip irrigation. A system is selected on an individual basis depending upon the land capability, cost, and farmer's choice. One drip system has been installed to irrigate mature orange trees and young lemon trees on sandy soils. The system components of the 100-acre system include a regulating reservoir, two miles of polyvinyl chloride pipe and 109 miles of polyethylene tubing. To date no sprinkler systems have been installed.

On flood systems, precision leveling of the field surface is a must if we are to achieve the degree of water control necessary to achieve high irrigation efficiency. Fields are surveyed on a 100-foot grid and designed with a flat grade. Construction specifications call for a tolerance of one-tenth foot from high to low on 80 percent of the field shots. Most of the earth is moved with heavy construction equipment.

Finish leveling is accomplished by using a laser controlled system. The control unit is a laser beam that rotates five to ten times a second. A receiving unit is mounted on a drag scraper which activates the scraper's hydraulic system to control the elevation of the blade. Fields checked after laser leveling are within one-tenth foot from high to low on all shots. Some have checked to within five hundredths foot from high to low.

Soils within the Wellton-Mohawk Irrigation and Drainage District vary in texture from fine sand to clay, often within the same field. Where this condition exists water intake rates obviously vary.

On fields where this is a problem, the areas of problem soils are excavated to a depth of 18 inches minimum and back filled with suitable soil. The excavated material is either wasted off site or mixed with soils on the rest of the field to achieve uniformity.

The final and perhaps most critical step in achieving high irrigation efficiency is the precision handling of the water. Good irrigation water management requires that the irrigator have a practical knowledge of soils, consumptive use, flow rates, basin size, crop response, gross and net water application needed and frequency of irrigation. An irrigation water management plan is developed and made a part of each contract. The plan includes a table listing the application time needed for each unit to be irrigated depending upon the quantity of water available (Table 1). Another chart describes the normal irrigations required per month and the net amount of each irrigation.

There is only limited data available on the effects of the program because only a few farmers have completed the on-farm installations and subsequently completed crop seasons on the same land. As of July 30, 1976, the following efficiencies are shown for farms having completed their treatment.

CROP	*ACREAGE*	*PRE-TREATMENT 1974-75 AVERAGE EFFICIENCY*	*POST TREATMENT 1976 EFFICIENCY*
Wheat	293	52%	79%
Alfalfa	216	65%	92%

REFERENCES

1. The Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District. 1974. Special Report on Measures for Reducing Return Flows from the Wellton-Mohawk Irrigation and Drainage District.

2. Soil Conservation Service National Engineering Handbook, Section 15, Irrigation, Chapter 4, Border Irrigation.

TABLE 1

Farm Irrigation Guide, October, 1975

	Field: 1, 13.1 Acre Level Borders *NET APPLICATION*								***Field: 2, 12.3 Acre Level Borders*** *NET APPLICATION*							
	0.3 Inch Intake Family								*0.5 Inch Intake Family*							
	3"		*4"*		*5"*		*6"*		*3"*		*4"*		*5"*		*6"*	
CFS	*hr*	*min*	*hr*	*min*	*hr*	*min*	*hr*	*min*	*hr*	*min*	*hr*	*min*	*hr*	*min*	*hr*	*min*
12	3	40	4	50	6	05	7	15	4	10	5	05	6	00	6	50
13	3	20	4	30	5	35	6	45	3	45	4	35	5	30	6	20
14	3	05	4	10	5	10	6	15	3	30	4	15	5	00	5	50
15	2	55	3	50	4	50	5	50	3	10	3	55	4	40	5	25
16	2	45	3	40	4	30	5	25	3	00	3	40	4	20	5	05
17	2	35	3	25	4	15	5	10	2	45	3	25	4	05	4	50
18	2	25	3	15	4	00	4	50	2	35	3	10	3	45	4	35

"Developed using Soil Conservation
Service National Engineering
Handbook, Section 15, Irrigation
Chapter 4, Border Irrigation" (2)

Research and Demonstration Approach to Development of Appropriate Salinity Control Technologies for Grand Valley

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ABSTRACT

Introduction of channel seepage and irrigation percolation losses into the underlying soils and marine aquifer, and the eventual return of these flows to the Colorado River with their large salt loads, make the Grand Valley in western Colorado one of the more significant salinity sources in the Upper Colorado River Basin. The Grand Valley Salinity Control Demonstration Project was formulated to delineate the magnitude of the water and salt flow components from the irrigation system, to evaluate the effectiveness of various water management technologies in reducing the salt load reaching the Colorado River, and to demonstrate appropriate technologies on farmers' fields.

Colorado River Salinity

The most serious water quality problem in the Colorado River Basin (Fig. 1) is salinity. Often referred to as mineral quality or mineral pollution, salinity concentrations progressively deteriorate towards the lower reaches of the river system resulting in significant economic penalties to Lower Basin users.

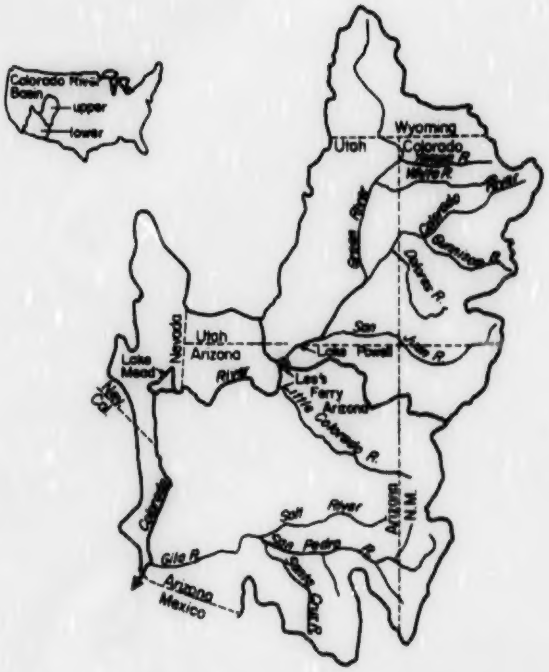
Colorado River Basin
upper
lower
Wyoming
Utah
Colorado
White R.
Green River
Colorado
Gunnison R.
Dolores R.
San Juan R.
Lake Powell
Utah
Arizona
Nevada
Lake Mead
River
Lee's Ferry
Arizona
Little Colorado R.
Colorado
Salt River
San Pedro R.
Santa Cruz R.
Gila R.
Arizona
N.M.
Arizona
Mexico

Figure 1. The Colorado River Basin.

Analysis of many years of data indicate the bulk of the Lower Basin salinity problem is attributable to the salt loads acquired in the Upper Basin. Therefore, salinity management in the Upper Basin must deal directly with controlling the salt loads in the river contributed by municipal, industrial, and agricultural water uses as well as some natural sources. However, most of the future water developments planned in the Upper Basin are directed toward meeting the rapidly expanding urban demands which lie outside of the Colorado River Basin. Thus, the export of this high quality water from the basin will significantly increase salinity concentrations throughout the basin by reducing the dilution capacity of the stream. These developments will have to be accompanied by associated reductions in the total salt load passing downstream resulting from salinity control programs to avoid further downstream damages.

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Although such salinity control alternatives as reducing reservoir evaporation and phreatophyte consumption will eventually be considered, the first priority is the reduction of salinity associated with agricultural return flows, presently constituting 37% (Fig. 2) of the total salt load from the Upper Colorado River Basin (EPA, 1977). The major aspects include conveyance channel linings, improving the on-farm water use efficiency, more stringent water controls by irrigation companies, and effective coordination of local objectives between the various organizations. The definitions and the interpretation of western water right laws pose a difficult obstacle to salinity control incentives for water users and thus must also be evaluated.

Among the most significant salt sources in the Upper Basin region is the Grand Valley (Fig. 3) in west-central Colorado. The area was selected for a detailed study of important parameters in the hydro-salinity flow system in order to quantify the sources of the valley salt contribution to the stream system. The detail of the investigation also made it possible to quantify the salinity control feasibility of several alternatives such as water conveyance channel linings and irrigation scheduling.

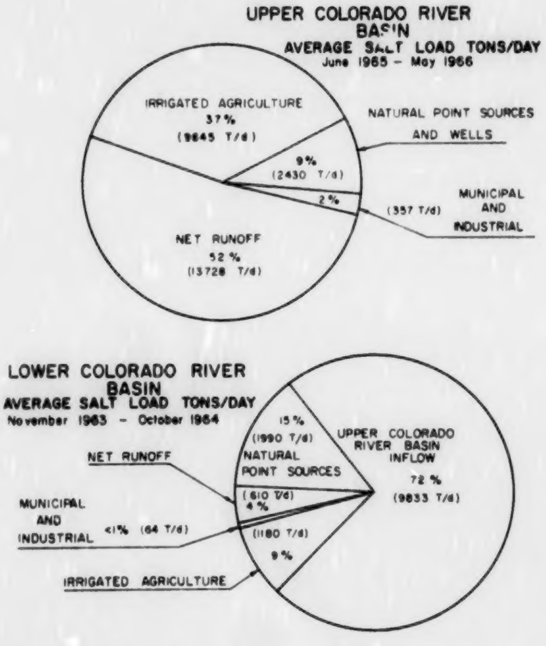

Figure 2. Major sources of salinity in the Colorado River Basin (U.S. Environmental Protection Agency, 1971).

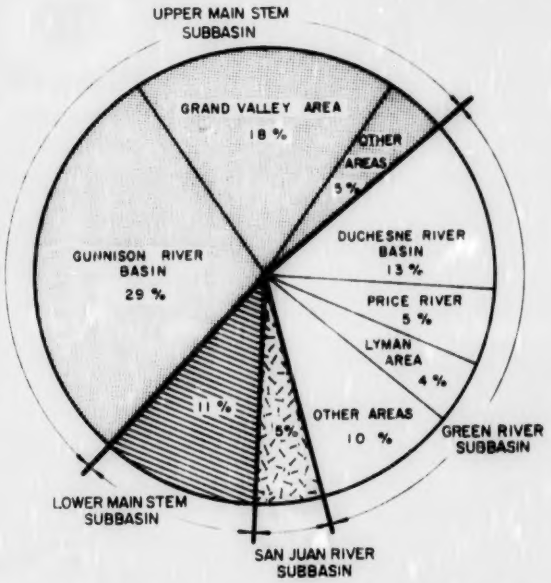

Figure 3. Relative magnitude of agricultural salt sources in the Colorado River Basin (U.S. Environmental Protection Agency, 1971).

The relative contribution from the valley to the total salt load in the upper river system attributable to agriculture is approximately 18% (Fig. 3), or between 0.6 and 0.9 million metric tons of salt annually (Hyatt, 1970 and EPA, 1971). Usually called "salt pickup," this contribution results from water contact with the naturally saline soils and aquifers overlying a marine deposited Mancos Shale formation. The shale, which is also the origin of much of the soils, contains numerous lenses of salt and can be readily dissolved. The introduction of water into these soils and aquifers from irrigation sources produces hydraulic gradients which displace groundwater into the river. Since this displaced water has usually had sufficient contact time to reach chemical equilibrium with the ambient salinity concentrations, large quantities of salts are added to the river.

General Approach

The Colorado River enters the Grand Valley from the east, is joined by the Gunnison River at Grand Junction, Colorado, and then exits to the west. The primary source of salinity is from the extremely saline aquifers overlying the marine deposited Mancos shale formation. The shale is characterized by lenses of salt in the formation which are dissolved by water from excessive irrigation and conveyance seepage losses when it comes in contact with the Mancos shale formation. The introduction of water through these surface sources percolates into the shallow groundwater reservoir where the hydraulic gradients it produced displace some water into the river. This displaced water usually has sufficient time to reach chemical equilibrium with the salt concentrations of the soils and shale. These factors also make the Grand Valley an important study area, since the conditions encountered in the valley are common to many locations in the basin.

In order to adequately define the water and salt flow system, both in terms of surface flows and subsurface flows, and taking into consideration available resources, it was necessary to designate a demonstration area. This area could be more intensely investigated than if the entire valley were measured for water and salt transport. Therefore, one of the requirements for such a demonstration area would be that it is representative of the irrigated lands in the Grand Valley.

Since salinity is really a problem involving subsurface irrigation return flows, then considerable knowledge must be gained regarding the groundwater hydrology. Also, one of the more difficult aspects of evaluating the effectiveness of improved irrigation water management practices for reducing the salt pickup returning to the Colorado River is being able to define the salt transport occurring in conjunction with moisture movement through the soil profile.

Basically, reducing the salt loading from Grand Valley will require a reduction in the volume of groundwater flows returning to the Colorado River. Consequently, the investigation must establish the sources of groundwater flow (e.g., canal seepage, lateral seepage, deep percolation losses, phreatophyte consumptive use, etc.). The next paper, "The Hydro-Salinity System in the Grand Valley" presents the results of these studies.

After developing a knowledge of the surface hydrology and subsurface hydrology, including the sources of groundwater flows, the next crucial step is to establish the chemical changes that occur as moisture moves through the soil profile into the groundwater reservoir. In Grand Valley, this step was accomplished by using a number of research plots which served as large-scale lysimeters. These plots are discussed below and the results are reported in the case study paper, "Modeling Salt Transport in the Irrigated Soils of Grand Valley."

With the above information, it then becomes possible to evaluate the effectiveness of a variety of water management technologies in reducing the salt load reaching the Colorado River. For Grand Valley, most of the salt load is the result of present irrigation practices. Therefore, the field studies must evaluate each of the appropriate technologies for improving irrigation water management by establishing the reduction in groundwater flow for each technology and then predicting the salt load reduction in the Colorado River. By evaluating such technologies on farmer's fields, it becomes possible to gain some measure of the acceptability of each technology, or combination of technologies, by the farmer. The final two papers in this case study, "Evaluating Appropriate Technologies for Salinity Control in Grand Valley" and "Development of Best Management practices for Salinity Control in Grand Valley" present the results of this phase of the research and demonstration program.

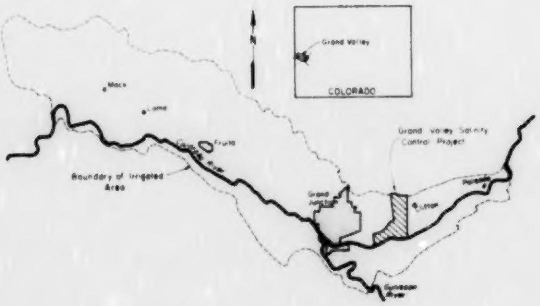

Figure 4. The Grand Valley of Colorado.

The Demonstration Area

The demonstration area, shown in Fig. 4, was chosen as an intensive study area in which the bulk of the investigation was to be conducted and also includes most of the construction and demonstration efforts. This area was designated for detailed investigations regarding various salinity control measures on the water and salt flow systems in an irrigated area. The intensive study area was selected for its accessibility in isolating most of the important hydrologic parameters, but also has the important advantage that it allowed five irrigation companies to participate in one unit.

In undertaking the Grand Valley Salinity Control Demonstration Project, one of the first tasks was to conceptualize a hydro-salinity model of the intensive study area (Fig. 5). This model has to have sufficient sensitivity to detect the effects of various salinity control measures upon the salt pickup reaching the Colorado River. Then, the model could be used to design the field data collection system. Finally, the model could be used to extrapolate results from the intensive study area to the entire Grand Valley.

A difficulty often encountered while preparing water and salt budgets is the variability in the accuracy and reliability with which the hydrologic and salinity parameters are measured. Usually, the mesurement precision varies with the scope of the research and the area of the study. The intensive study area on this project has been observed in great detail.

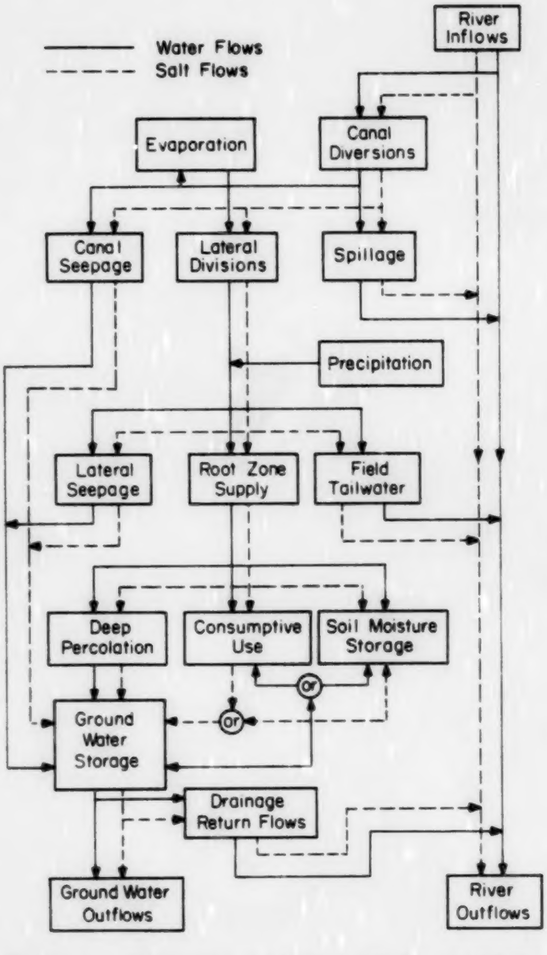

Figure 5. Schematic of hydro-salinity model for Grand Valley.

Since the hydrologic system is difficult to monitor and predict, it is impractical to expect models to operate without applying some adjustments in order that all components will be in balance. In short, the budgeting procedure is usually the adjustment of the segments in the water and salt flows according to a weighting of the most reliable data until all parameters represent the closest approximation of the area that can be achieved with the input data being used. The vast and lengthy computation procedure of calculating budgets is facilitated by a mathematical model programmed for a digital computer. A complete listing and explanation of its operation has been previously reported (Walker, 1970).

The discussion below is intended to give the reader some insight into the types of field investigations that were undertaken in order to develop a hydro-salinity model calibrated for the Grand Valley Salinity Control Demonstration Project area, yet capable of predicting water and salt flows for the entire Grand Valley.

Field Investigations

The effects of poor water management are significant in the study area as 50% of the irrigable acreage has been reduced to marginal production because of high water tables. The hydrologic factors responsible for these conditions were that they could be studied in reasonable detail. In this investigation, a balance between physical size of the area, level of funding, and the detail with which the system parameters, could be studied resulted in an experimental design consisting of two phases: (i) instrumentation and (ii) peripheral investigations.

The instrumentation in the area (Fig. 6) provided valuable data describing much of the water and salt movement. Some parameters such as drainage discharges, lateral diversions, water quality, and precipitation could be measured directly. Other parameters such as groundwater movements, deep percolation, and evapotranspiration were computed from data supplied by piezometers, wells, soil sample analyses, and climatologic data.

Many of the water and salt subsystems do not readily lend themselves to direct measurement and must be quantified from an examination of a sample of the area, in which it is assumed that the sample is representative of the whole. Such studies included farm efficiency in which the proportions of evapotranspiration, deep percolation, tailwater runoff, and soil moisture storage were evaluated, along with the resulting changes in salinity.

Instrumentation

The hydrostatic pressures through the soil profiles, hydraulic gradients, and conductivities were determined by numerous clusters of 0.95-cm diameter steel pipe piezometers. In each cluster, three to seven piezometers were located at varying depths depending on the textural changes encountered in the placement of the first piezometer to as great a depth as possible. The technique used to extend the piezometers employed a jetting rig which pumped water at moderate pressure through the pipe to jet material away from the end of the piezometer.

Because the small piezometers were limited to the soil profiles, the examination of water and salt movements in the underlying cobble aquifers was facilitated by drilling 5-cm diameter wells into these strata. The bottoms of the pipes extended to the top of the Mancos Shale formation in most cases, but several wells were extended only midway through the aquifer or just into the top in order to test the differences that may exist in the conditions in the aquifer. The function of these instrument points was essentially the same as that of the small piezometers. The large diameters facilitated both depth measurements and water sampling.

Small Parshall and Cutthroat flumes were used in the study to monitor discharges in the drainage system. They were also extensively used as part of the special studies on farm efficiency, lateral ditch seepage, and farm water deliveries. At the most important locations, flumes with continuous stage recorders were installed to minimize the error in evaluating the discharges. Both types of flumes involve primarily free flow operation, but continual maintenance was required to maintain this condition as mossing, sediment, and bank vegatation created considerable submergence effects as the study progressed.

An essential element of the analysis was the measurement of the water diverted from the canal system into the farm laterals for irrigation. In the smaller capacity canals where the discharges rarely exceed 1.4 m^3/sec, the inlets and exits to the study area were rated by correlating current water measurements with the stage in the canal. One exception to this was at the inlet to the Mesa County Ditch in which a 1.5-m submerged orfice was calibrated. The discharges in two of the main canals were of the order of 17 m^3/sec and it was felt that even if a 2 to 5% inlet and exit rating could be developed, this error would mask most of the diversions to the cropland. To remedy this situation, the farm turnouts from each canal were individually rated. Prior to the irrigation season, the relation between thread rod height and gate opening for each of the culvert-type turnouts was determined. The rating procedure involved the placement of a portable Parshall flume downstream from the gate to measure the flow, thereby producing a rating curve with less than a man-day of effort.

Peripheral Investigations

A number of segments within the water and salt flow system could not be measured with the available instrumentation and special studies were required. The first such special study was the determination of the seepage rates from the canal and lateral systems. The ponding method, which involves diking the canal or lateral into several ponds and then correlating the falling water surfaces to seepage rates, was selected to assure accurate measurements. However, in many of the smaller laterals the inflow-outflow method was employed. The use of the two methods depended on the discharge capacity of the conveyance channel.

In order to evaluate the quantity of water being evaporated and transpired from the soil and crop surfaces, a detailed land use inventory of the Grand Valley was conducted. The procedure involved carrying aerial photos (1 cm = 120 m) into the field and making note of the various land uses on them. Then each crop area was determined by measuring the respective area on the photo (Walker and Skogerboe, 1971).

The water and salts being applied to the cropland either result in tailwater, deep percolation, or root zone storage. To delineate these components, farm efficiency studies were conducted on typical farms. Inflow-outflow measurements and soil moisture samples were taken to identify the water and salt movements.

Other smaller studies were made to determine the effectiveness of the existing drainage system and the subsurface soil and aquifer characteristics. These investigations proved to be helpful in understanding the hydrologic network and added confidence to the results.

Soil Chemistry Research Plots

The hydro-salinity model describes the present situation in the study area regarding water and salt flows. However, the only method for predicting the reduction due to salinity control measure(s) is by assuming a one-to-one relationship between water and salt. That is, if the subsurface return flow is reduced by 50%, the salt is also reduced by 50%. In order to overcome this limitation, a project "Irrigation Practices, Return Flow Salinity, and Crop Yields" was initiated.

Three adjacent fields containing 23 acres was leased for this study. The area was divided into 54 plots which are 100 feet by 100 feet in size, two plots which are 40 feet by 200 feet, two plots which are 40 feet by 300 feet, and five plots which are 40 feet by 500 feet. Each plot is used for a different replication of the crop, fertilizer and irrigation treatments. They were constructed so that each plot performs as a large lysimeter. A trench was excavated slightly into the shale along the lines dividing the plots. A plastic curtain was then placed vertically in the center of the trench to divide the individual plots. The lower edge of the curtain is "sealed" to the shale by back-filling to the original elevation of the shale with compacted clay. The average depth to shale is approximately ten feet.

The drainline encased in a gravel filter material was then placed inside the curtain and continued around the periphery of the plot. Upon leaving the plot area, the water is transported via solid pipeline to a measuring station where water quality and quantity is monitored.

The irrigation system is designed to deliver water through a closed conduit to each plot and allow measurement of the flows onto each plot. Since furrow irrigation is used almost exclusively throughout the valley, this method has been employed on the project area.

The crops being grown are corn, grass, alfalfa, and winter wheat, since these are the main crops grown commercially in the valley. By varying irrigation timing and amounts, crops, and nitrogen fertilizer levels on the different plots, and by monitoring quality and quantity of both inflow and outflow waters, the effects of these parameters on return flow salinity and crop yields can be evaluated.

The third paper in the case study, "Modeling Salt Transport in the Irrigated Soils of Grand Valley" reports the results of this phase of the research program.

Demonstration of Salinity Control Measures

The principal study area in Grand Valley (Fig. 4), was first used for evaluating the effectiveness of canal and lateral lining, as well as irrigation scheduling and tile drainage in reducing the salt load entering the Colorado River. Later, the same area was used as a demonstration project during the 1974, 1975, and 1976 irrigation seasons. The advantage in continuing to utilize this study area is that the hydrology is already known. The wealth of available information provides a strong basis for evaluating the effectiveness of salinity control measures.

With the available knowledge regarding the study area, a lateral including the associated land served by the lateral water supply was used as a sub-system for evaluating the salinity reduction in the Colorado River resulting from the implementation of a salinity control technology package. In order to facilitate continued participation by most irrigation interests in Grand Valley, this demonstration project utilized laterals under each of the five canals in the study area. These particular laterals were selected to represent a wide variety of irrigation and drainage problems.

The selection of a lateral as a sub-system, rather than an individual farm, has a tremendous advantage in allowing control at the lateral turnout. In this way, both the quantity of flow and the time of water delivery can be controlled, thereby facilitating improved water management throughout the subsystem.

The most significant aspect of this particular demonstration project was the employment of a salinity control technology "package", rather than a single control measure. Experience in Grand Valley has shown that the most significant progress is made when the gamut of questions can be answered regarding the interrelationships between water management and agricultural production. Thus, the concept of a technology package, along with an understanding of the "system" including other agricultural inputs, provides the necessary base for providing sound advice to the farmer, which in turn facilitates the development of credibility and consequently farmer acceptance.

This phase of the research and demonstration program is reported in the fourth paper of this case study, "Evaluating Appropriate Technologies for Salinity Control in Grand Valley."

Best Management Practices

The results from the demonstration project will be projected to valley-wide conditions in developing best management practices for salinity control in Grand Valley. This will integrate several years of concentrated study in the valley and will serve as a basis for an action salinity control program. Such a program would detail the optimal strategy for implementing various levels of individual salinity control measures into a comprehensive technology package. To develop this kind of policy, cost-effectiveness functions relating the reductions in the system salt loadings resulting from a specified investment would be individually assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of salinity control. Since salinity control in Grand Valley must evolve with the development of water resources in the Upper Colorado River Basin, the time-varying characteristics of salinity control strategies must be described. The results of this optimization are described in the final paper of this case study, "Development of Best Management Practices for Salinity Control in Grand Valley."

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The Hydro-Salinity System in the Grand Valley

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ABSTRACT

The Grand Valley hydro-salinity system is described by research data collected over an eight-year period. A review of previous estimates indicates the great variability that can be expected when data are few and of poor quality. The Grand Valley system contributes approximately 630,000 metric tons of salts to the river annually. This figure represents 78 metric tons of salt per hectare-meter of water reaching the underlying groundwater aquifer from irrigation return flows with canal and ditch seepage contributing 23 percent of the salt pickup, lateral seepage 32 percent, and on-farm head ditch seepage and deep percolation losses contributing the remaining 45 percent of the salt pickup.

INTRODUCTION

In the mid-1960's, a concerted effort was undertaken to identify the sources of salinity in the Colorado River Basin. The Federal Water Pollution Control Administration, then within the Interior Department, utilized U.S. Geological Survey stream gaging data as well as an extensive water quality sampling program to identify the major salt contributors in the basin (U.S. Environmental Protection Agency, 1971). The Grand Valley in western Colorado was described as one of the largest agricultural sources of salinity (about 18% of the total Upper Basin's agriculturally related contribution), and it subsequently became the site for the first studies to evaluate field-scale salinity control measures. The involvement by Colorado State University has been summarized by Skogerboe and Walker (1972) and Skogerboe et al. (1974a).

The early studies identified the Grand Valley as a major problem area by mass balancing water and salt flows into and out of the valley region. Similar investigations by Iorns et al. (1965) and Hyatt et al. (1970) produced supportive results, although a substantial variability in the specific nature of the Grand Valley salinity problem emerged. Since that time, a great many individual calculations describing the valley salt loading and the respective components have been made, but very little agreement existed until early 1977 when most studies were completed. Although some variability still exists among the various investigative groups, the differences are sufficiently close that they become relatively unimportant in determing the overall Best Management Practices for the Grand Valley as will be shown in the last paper of this case study.

The purpose of this paper is to describe the Grand Valley hydro-salinity system as existing data defines it, and in so doing, hopefully provide some insight into how various data might be interpreted in agriculturally related water quality studies.

HYDRO-SALINITY BUDGETING

The procedures for delineating the water-salt flow system in an irrigated area is termed hydro-salinity budgeting, or hydro-salinity modeling, since computers are generally needed to handle the large number of necessary calculations. In the Grand Valley, the composition of this system has been extensively investigated at various levels of sophistication. As the salinity investigations were continued, refinements in the valley's basin-wide impact have been made and verified. Interestingly, the research evolution in the Grand Valley case study suggests a fairly sound approach for other areas as well.

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The problem of remedying an irrigation return flow problem causing detrimental water quality deterioration can be divided into four logical steps. First, the magnitude of the problem and the downstream consequences must be identified in relation to the irrigated area's individual contribution to the problem. In this way, the most important areas can be delineated for further consideration, thereby making the most cost-effective use of available personnel and funding resources. As noted previously, this step led to the exhaustive efforts in the Grand Valley that this case study reports. Next, the components of the problem must be segregated. In most large areas, the cost of studying the entire system are prohibitive, so smaller "sampling" studies are conducted from which projections are made to predict the behavior of the entire area. The next step is to evaluate management alternatives on a prototype scale in order to assess their cost-effectiveness and develop a sensitivity about the capability for implementing such technologies. And finally, if the measures which can be applied are effective in reducing salinity and economically feasible, the final step is the actual application of the technology to solving the water quality problem. This paper summarizes the first two of these steps as they developed in the Grand Valley.

PROBLEM IDENTIFICATION

The Grand Valley was identified as an important agricultural source of salinity in the Colorado River Basin through a series of analyses involving mass balance of the valley inflows and outflows. Iorns et al. (1965) evaluated stream gaging records for the 1914 to 1957 period, concluding that net salt loading (salt pickup) from irrigation in the valley ranged from about 450,000 to 800,000 metric tons annually. This range of numbers has been generated independently by Hyatt et al. (1970), Skogerboe and Walker (1972), Westesen (1975), and the U S. Geological Survey (1976). More recent consideration of data by the writers and others indicates a long-term salt pickup rate between 600,000 to 700,000 m tons/year. This figure is now generally accepted by the various research groups and action agencies involved with Grand Valley salinity investigations.

The fact that the valley's salinity contribution has been such a disputed figure over the last five years exemplifies the importance of establishing the total valley contribution. In areas like the Grand Valley where the total valley impact is only 5-8% of the river inflows or outflows, the impact of irrigation must be established using statistical analyses of the available data. However, the natural variability can cause serious errors in conclusions regarding salt pickup if not tempered by other data. For example, a major problem in early investigations was deciding how much of the inflow-outflow differences were due to natural runoff from the surrounding watershed. Because of the meager precipitation locally, the writers assumed the natural salt contribution would be negligible. This conclusion was later substantiated partially by Elkin (1976) who estimated an upward limit for the natural contribution of about 10% of agricultural figures.

SEGREGATING THE IRRIGATION RETURN FLOW SYSTEM

In the Grand Valley, as in numerous other irrigated areas, water is supplied to the cropland in a canal, ditch, and lateral conveyance system. Water is diverted from the Colorado and Gunnison Rivers into three major canals: (1) the Government Highline Canal; (2) the Grand Valley Canal; and (3) the Redlands Power Canal. These large canals in turn supply the smaller canals and ditches as follows:

Government Highline Canal	Grand Valley Canal	Redlands Power Canal
Stub	G. V. Mainline	Redlands #1
Price	G. V. Highline	Redlands #2
Orchard Mesa Power	Mesa County	
Orchard Mesa #1	Kiefer Extension	
Orchard Mesa #2	Independent Ranchmen's	

A description of the hydraulic characteristics of these canals and ditches is given in Table 1, based on information provided by the Bureau of Reclamation. From the canals and ditches, water is diverted into the small, largely earth ditches leading to the individual fields. This lateral system involves approximately 600 kilometers of ditch carrying from 0.06 m^3/sec to 1 m^3/sec. A frequency distribution of the lateral lengths based on data provided by the Bureau of Reclamation is given in Figure 1 indicating that the average length is about 400 meters. The average capacity is about 0.10 m^3/sec.

Nearly all farmers in the valley apply water using the furrow irrigation method. The Soil Conservation Service extensively inventoried the valley's irrigation system and were kind enough to make that data available for use herein. There are over 9000 individual fields in the Grand Valley having widths, slopes and lengths as distributed in Figures 2, 3, and 4. Thus, the typical field is 140 meters wide, 160 meters long, with a slope (toward the south generally) of 1.125%. A frequency distribution of field acreages is given in Figure 5 showing the typical field encompassing about 2 hectares. Calculating the length of unlined field head ditches based on the SCS data indicates a total length of 1300 kilometers. Tailwater ditch length would approximate head ditch length.

TABLE 1

Hydraulic characteristics of the Grand Valley canal and ditch system.

Name	*Length (km)*	*Initial Capacity (m^3/sec)*	*Terminal Capacity (m^3/sec)*	*Initial Perimenter (m)*
Government Highline Canal	73.70	16.99	0.71	19.19
Grand Valley Canal	19.80	18.41	14.16	16.67
Grand Valley Mainline	21.70	7.08	0.71	13.86
Grand Valley Highline	37.00	8.50	3.96	12.62
Kiefer Extension of Grand Valley	24.50	3.96	0.71	7.25
Mesa County Ditch	4.00	1.13	0.06	6.67
Independent Ranchmen's Ditch	17.40	1.98	0.85	3.17
Price Ditch	9.50	2.83	0.28	7.27
Stub Ditch	11.30	0.85	0.11	2.94
Orchard Mesa Power Canal	3.90	24.07	24.07	18.20
Orchard Mesa #1 Canal	24.10	3.12	0.17	6.46
Orchard Mesa #2 Canal	26.10	1.98	0.17	3.58
Redlands Power Canal	2.90	24.07	24.07	16.88
Redlands #1 & #2 Canals	10.80	1.70	0.06	3.95

Irrigation water is applied to approximately 25,000 hectares during the course of a normal irrigation season (Walker and Skogerboe, 1971). This acreage has been substantiated by the recent SCS inventory and generally accepted by the other agencies. A graphical breakdown of the acreage and miscellaneous land use in the valley is given in Figure 6.

Based upon lysimeter data reported by Walker et al. (1976) the weighted average consumptive use demand by the irrigated portion of the area equals about 0.745 meters per season. These evapotranspiration estimates when applied to all of the respective demands in the Grand Valley are indicated in Table 2.

The irrigation return flow system in the valley may be divided according to whether or not the return flows are surface or subsurface flows. Surface flows occur as either field tailwater or canal, ditch, and lateral spillage. Subsurface flows include canal and ditch seepage, lateral seepage, and deep percolation from on-farm water applications (deep percola-

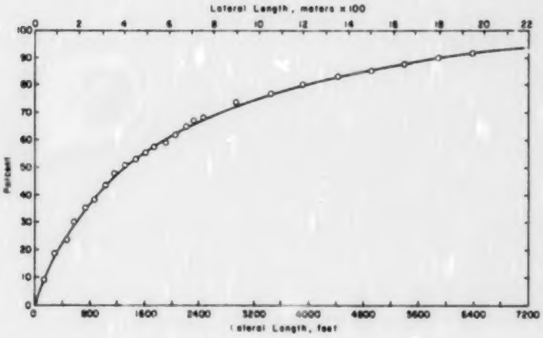

Figure 1. Frequency distribution of lateral lengths in the Grand Valley.

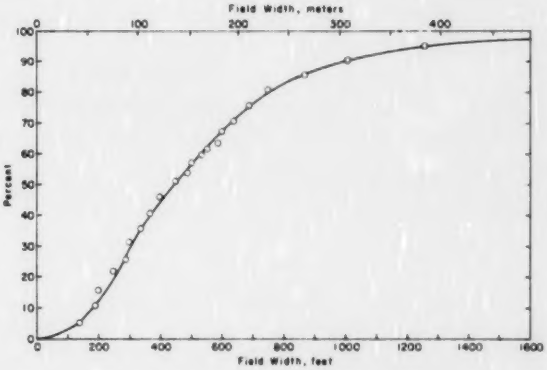

Figure 2. Frequency distribution of field widths in the Grand Valley.

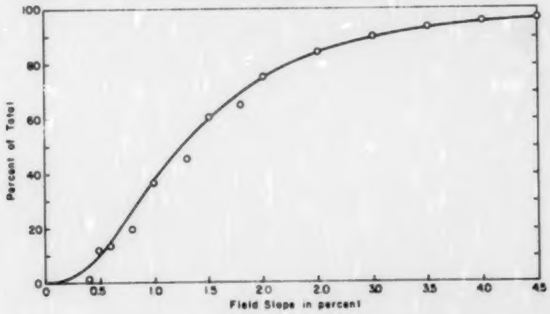

Figure 3. Frequency distribution of field slopes in the Grand Valley.

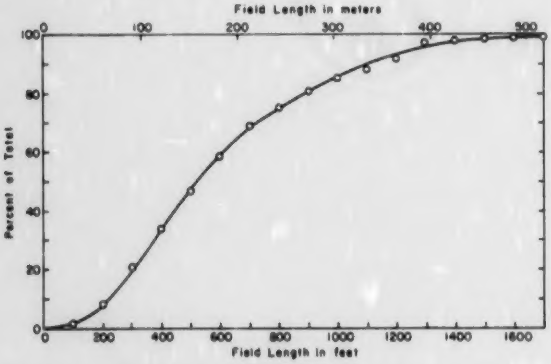

Figure 4. **Frequency distribution of field lengths in the Grand Valley.**

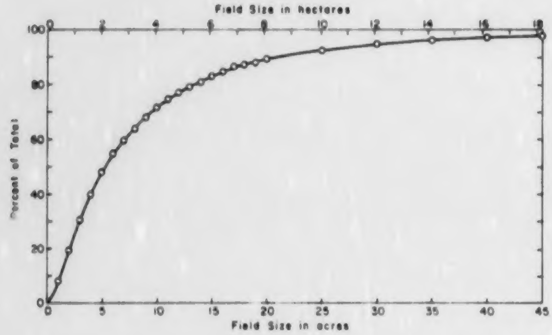

Figure 5. **Frequency distribution of field areas in the Grand Valley.**

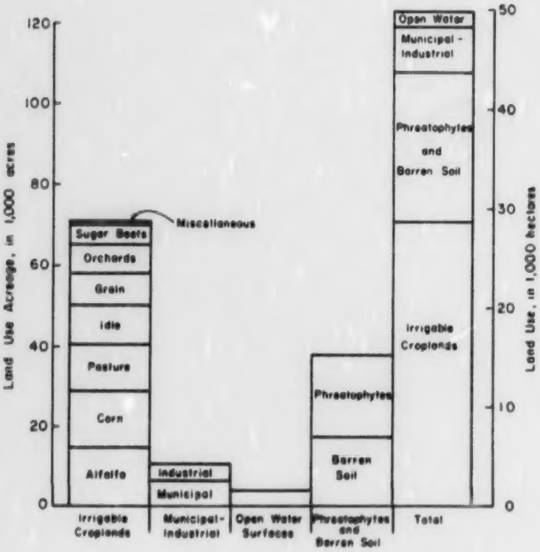

Figure 6. **Land use in the Grand Valley.**

TABLE 2

Consumptive use estimated for the Grand Valley.

Consumptive Use	*Volume in ha-m*	*Depth in Meters*
Open water surface evaporation and phreatophyte use[1]	3,450	0.138
Open water surface evaporation and phreatophyte use[2]	8,400	0.336
Cropland	18,600	0.745
TOTAL	30,450	1.219

[1] adjacent to river

[2] along canals and drains

tion includes head ditch and tailwater ditch seepage).

Canal and Ditch Seepage

Since the early 1950's, five major seepage investigations on the valley's major canals and ditches have been conducted (Skogerboe and Walker, 1972 and Duke et al., 1976). Seepage rates have been noted over a wide range, but representative rates are presented for the fourteen canal systems in Table 3. Walker (1977) developed a mathematical relationship describing seepage:

$$V_s = \frac{N_d \bullet WP_m \bullet S_r \bullet L}{2b} [1-(1-b)^2] \qquad (1)$$

in which

V_s = seepage volume of a canal in m^3/year;
N_d = number of days in operation per year;
WP_m = inlet wetted perimeter, m;
S_r = seepage rate, m^3/m^2/day;
L = canal length in m; and
b = empirical constant representing the fraction of maximum wetted perimeter remaining at the end of the canal

If the values in Table 2 are substituted into Eq. (1), the seepage volume for each canal and ditch can be determined (Table 1). In the Grand Valley, the writers estimate canal seepage to be approximately 3,700 ha-m per year.

TABLE 3

Seepage data for the fourteen major canal systems in the Grand Valley.

Name of Canal or Ditch	*Days in Operation*	*b*	*Seepage Rate m³/m²/day*	*Seepage Volume ha-m*
Government Highline	214	0.80	0.091	1652.53
Grand Valley	214	0.17	0.045	290.84
Grand Valley Mainline	214	0.69	0.061	257.16
Grand Valley Highline	214	0.29	0.061	521.16
Kiefer Extension	214	0.60	0.061	162.31
Mesa County	214	0.64	0.061	23.68
Independent Ranchmen's	214	0.31	0.061	60.84
Price	214	0.65	0.061	60.86
Stub	214	0.44	0.061	33.83
Orchard Mesa Power	365	0.001	0.076	196.80
Orchard Mesa #1	214	0.72	0.076	162.05
Orchard Mesa #2	214	0.62	0.076	104.86
Redlands Power	365	0.001	0.065	116.08
Redlands 1 & 2	214	0.67	0.137	83.17
				3726.17

Lateral Seepage

Tests reported by Skogerboe and Walker (1972) and Duke et al. (1976) indicate seepage losses from the small ditches comprising the lateral system probably average about 8.79 ha-m/km/year in the Grand Valley. Thus, for the 600 km of small laterals, the total seepage losses are 5273 ha-m annually (or approximately 5300 ha-m annually). Combined lateral and canal seepage is, therefore, approximately 9000 ha-m annually.

On-farm Deep Percolation

Numerous studies in recent years have attempted to quantify deep percolation from on-farm water use. Skogerboe et al. (1974a, 1974b) estimated these losses (including head ditch and tailwater ditch seepage) to be about 0.246 ha-m/ha. Duke et al. (1976) estimated these losses, independent of ditch seepage, to be 0.15 ha-m/ha. Although the earlier studies by the writers assumed negligible head ditch seepage (which is true for the test fields reported), it is probably correct to allow for these losses. The fact of the matter is, however, that many fields fit both assumptions and given the large number of fields tested by various investigators, total on-farm losses are probably about 7500 ha-m.

Canal Spillage and Field Tailwater

The operational wastes and field tailwater are difficult to define because, first, they do not generally create problems associated with salinity degradation, and second, data regarding these flows are sparse. Skogerboe et al. (1974b) listed field tailwater as 43% of field application whereas Duke et al. (1976) listed this percentage as 36%. On the other hand, Skogerboe et al. (1974b) and Duke et al. (1976) reported estimates of canal spillage as administrative wastes which were 18% and 35% of field applications, respectively. Estimates of spillage and tailwater by the Bureau of Reclamation were slightly smaller than the authors' estimate. Using the 43% figure for field tailwater and the 18% figure for canal spillage yields about 37,000 ha-m per year field tailwater and spillage.

Aggregating the data presented previously with inflow-outflow records in the vicinity of Grand Valley gives a clear picture of how the irrigation system relates to the overall hydrology (Figure 7). The flow diagram is particularly helpful in visualizing the relative magnitude of the irrigation return flows from the agricultural area.

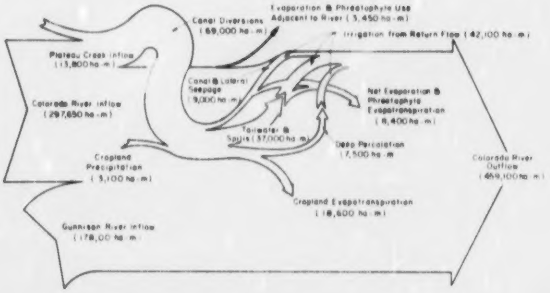
Canal Diversions (69,000 ha-m)
Evaporation & Phreatophyte Use Adjacent to River (3,450 ha-m)
Irrigation from Return Flow (42,100 ha-m)
Plateau Creek Inflow (13,800 ha-m)
Canal & Lateral Seepage (9,000 ha-m)
Colorado River Inflow (297,650 ha-m)
Net Evaporation & Phreatophyte Evapotranspiration (8,400 ha-m)
Tailwater & Spills (37,000 ha-m)
Deep Percolation (7,500 ha-m
Cropland Precipitation (3,100 ha-m)
Colorado River Outflow (459,100 ha-m)
Cropland Evapotranspiration (18,600 ha-m)
Gunnison River Inflow (178,00 ha-m)

Figure 7. Mean annual flow diagram of the Grand Valley hydrology.

IDENTIFYING THE SALINITY CONTRIBUTION

The salinity contribution of the Grand Valley hydro-salinity system can be developed in a number of ways. For example,

Net Salt Pickup	630,000 m tons/year
Net Groundwater Return Flow	8,100 ha-m/yr

$$\frac{\text{Pickup}}{\text{Return flow}} = 77.8 \ \frac{\text{m tons}}{\text{ha-m}} = 7{,}800 \text{ mg/l}$$

Data reported by Skogerboe and Walker (1972) indicate an average groundwater salinity of 8,000 to 10,000 mg/l (average of 8,700 mg/l) which compares favorably with the salt pickup rate of 7,800 mg/l plus an irrigation water salinity of 500-700 mg/l (say 600 mg/l) which gives a total predicted salinity concentration of 8,400 mg/l.

The U.S. Geological Survey and others have recently measured drainage return flows at selected areas in the valley. These data indicate an average salinity of 4,000 mg/l. Thus, as Duke et al. (1976) pointed out, if all return flows were through the drainage channels and phreatophyte consumptive use was not considered (as earlier assumptions are inappropriate concerning these losses), the calculation would be:

$$(\text{Deep Percolation} + \text{Seepage})\ (4{,}000\ \text{mg/l})\ (.01\ \frac{\text{ton/ha·m}}{\text{mg/l}}) = \text{Salt Pickup}$$

or

$$(16{,}500\ \text{ha-m})\ (40) = 660{,}000\ \text{m tons}$$

Consequently, the two salt loading figures, as predicted by inflow-outflow mass balancing and calculation using local data, check out.

Ignoring the effect of evapotranspiration (a concentrating effect), the following contributions to salinity loading (salt pickup) can be delineated:

Canal and Ditch Seepage	23%
Lateral Seepage	32%
On-farm Losses	45%

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Modeling Salt Transport in the Irrigated Soils of Grand Valley

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ABSTRACT

This study was undertaken to evaluate the effects of the volume of leachate leaving the soil profile on the quality of the leachate. A numerical salt transport model was selected for use in the study. Field data to calibrate the model were collected on 63 research plots located in the Grand Valley. The model was tested and calibrated with the field data and then used in a series of hypothetical simulations designed to provide the required information.

The modeling results indicate that the salt concentration of the leachate is independent of the volume of leachate. The six-year simulation showed that the concentration of salt below the root zone was relatively constant. Therefore, the salt loading due to subsurface irrigation return flows can be calculated from a water budget analysis, with salt load reductions being directly proportional to the reduced volume of subsurface return flow.

INTRODUCTION

Previous studies conducted on methods of salinity control in the Grand Valley assumed that the concentration of salt in the subsurface return flow was independent of the volume of the return flow. This implied that any method which reduced the volume of return flow would effect a similar reduction in the salt load. The current study was designed to evaluate the validity of this assumption. The first phase of the study was to evaluate a salt transport model using soil moisture and salinity data gathered in the Grand Valley. Once the evaluation was complete, the model was used to simulate a series of hypothetical irrigation treatments. Data from these simulations were used to evaluate the effect of the volume of return flow on the concentration of ionic species in the solution, both in the soil profile and leaving the soil profile. If the soil solution became saturated with a particular ionic species, then further salt pickup could be prevented as the return flow moved over the shale bed.

The focus of this particular study was the adaptation and evaluation of a numerical model which could be used to characterize the salt transport occurring in the soils of the Grand Valley. A numerical model developed by Dutt et al. (1972), which is currently being used by the Bureau of Reclamation, USDI (see earlier conference paper by Shaffer and Ribbens), was selected for use in the study. The method of calculating the value of hydraulic conductivity and diffusivity used in the difference equation of the soil water flow program was changed from that found in Dutt's model. Also, the functional relationships used to calculate hydraulic conductivity and diffusivity were changed. The soil water flow and soil chemistry data used in the evaluation of the model were collected as part of an on-going study in which the effect of irrigation on crop yields and salinity of deep percolation was investigated.

The research was conducted on 63 research plots located on a 9.3 hectare site in the Grand Valley. Eight irrigation treatments, four crops and two fertilization treatments were used to generate the moisture flow and salt transport data required to calibrate the numerical model. The irrigation schedules in the hypothetical simulations used either 7 or 14 day irrigation intervals and a depth of irrigation equal to the evapotranspiration in the interval plus a leaching increment which ranged from 1% to

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40% of estimated evapotranspiration. The evapotranspiration for the simulations was estimated using meteorological data collected in the Grand Valley in conjunction with the irrigation scheduling program of the Agricultural Research Service (Kincaid and Heerman, 1974).

SOIL CHEMISTRY MODEL

The primary objective is to model the transport of salts through the soils. (See Ayars, 1976, for a more thorough discussion.) The first portion of the flow of water and consequent transport of salts is through the root zone, which is usually a zone of partial saturation. A numerical model of the moisture flow and chemical and biological reactions occurring in the root zone has been developed by Dutt et al. (1972). (This reference contains a complete listing of the computer program.) This is the basic model which will be used to describe salt transport.

The model consists of three separate programs. The first program describes the soil moisture movement and distribution with time. The second program interfaces the soil moisture movements with the chemical-biological model. This is needed because the horizons used in the calculations of soil moisture and chemistry differ. The third program computes the chemical and biological activity occurring in the soil profile. Figure 1 is a block diagram of the over-all model. A brief description of the moisture flow and chemical-biological models is included to serve as a basis for understanding the data collection requirements.

The flow is one-dimensional and was developed using the Richards equation with a sink term. Schematically, the model is given in Fig. 2. Mathematically, the flow is described using Richards equation in the form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[\frac{D(\theta)\partial \theta}{\partial z} - K(\theta)\right] - S(E_t) \qquad (1)$$

where

θ = volumetric moisture content,

t = time,

z = space coordinate in vertical direction,

$D(\theta)$ = soil moisture diffusivity,

$K(\theta)$ = hydraulic conductivity,

$S(E_t)$ = evapotranspiration sink term (volume of water consumed per unit volume of soil per unit time).

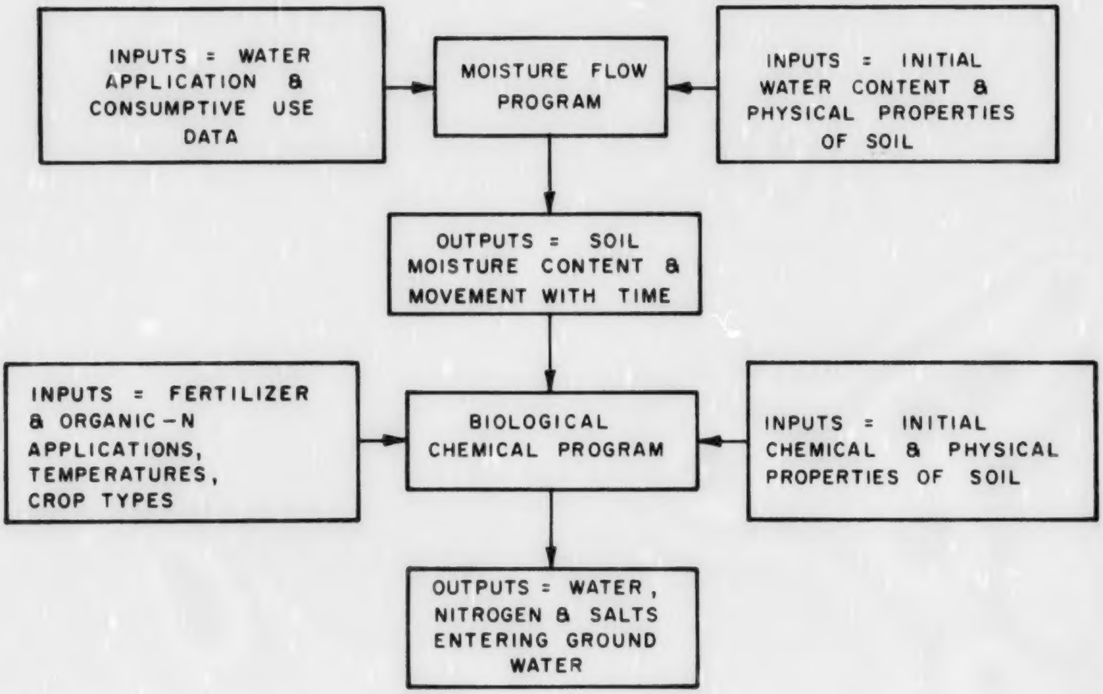
INPUTS = WATER APPLICATION & CONSUMPTIVE USE DATA
MOISTURE FLOW PROGRAM
INPUTS = INITIAL WATER CONTENT & PHYSICAL PROPERTIES OF SOIL
OUTPUTS = SOIL MOISTURE CONTENT & MOVEMENT WITH TIME
INPUTS = FERTILIZER & ORGANIC-N APPLICATIONS, TEMPERATURES, CROP TYPES
BIOLOGICAL CHEMICAL PROGRAM
INPUTS = INITIAL CHEMICAL & PHYSICAL PROPERTIES OF SOIL
OUTPUTS = WATER, NITROGEN & SALTS ENTERING GROUND WATER

Figure 1. Generalized block diagram of the model.

This is the diffusivity form of the equation which means that only flow in the partially saturated zone of the soil profile can be described. The evapotranspiration sink term, $S(E_t)$, is computed using the Blaney-Criddle equations for evapotranspiration (other equations could be adapted to the model such as the root extraction term reported by Hanks, Willardson and Melamed earlier in this conference) with the loss due to evapotranspiration being distributed through the soil profile by assuming a specific root distribution for the crop. The root distribution and coefficients for the Blaney-Criddle equations are supplied by the user. Actual values of evapotranspiration can be used in the sink term when they are known.

Salt transport is described by the following equation in one dimension.

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z} \left(\theta D \frac{\partial c}{\partial z}\right) - \frac{\partial (vc)}{\partial z} + S \qquad (2)$$

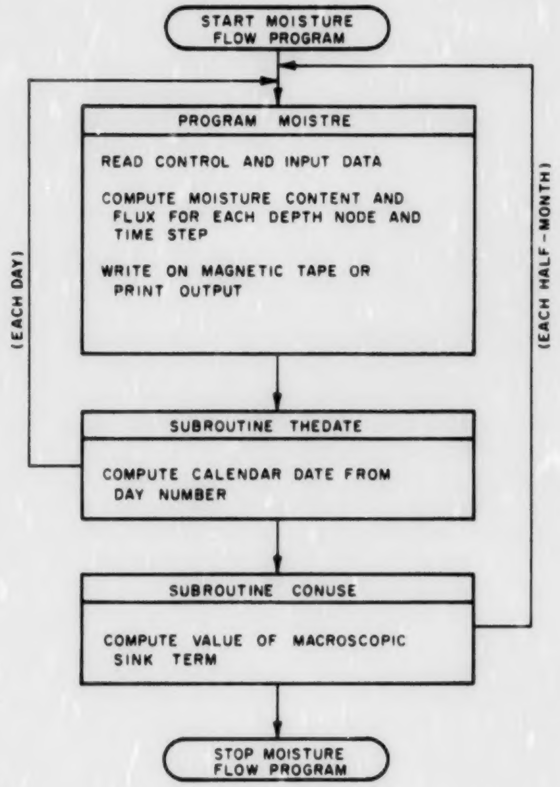
START MOISTURE FLOW PROGRAM
PROGRAM MOISTRE
READ CONTROL AND INPUT DATA
COMPUTE MOISTURE CONTENT AND FLUX FOR EACH DEPTH NODE AND TIME STEP
WRITE ON MAGNETIC TAPE OR PRINT OUTPUT
(EACH DAY)
(EACH HALF-MONTH)
SUBROUTINE THEDATE
COMPUTE CALENDAR DATE FROM DAY NUMBER
SUBROUTINE CONUSE
COMPUTE VALUE OF MACROSCOPIC SINK TERM
STOP MOISTURE FLOW PROGRAM

Figure 2. Generalized block diagram of Moisture Flow Program.

where

c = solute concentration,
D = diffusion-dispersion coefficient,
v = volumetric flux given by Darcy's Law,
S = source or sink term for the chemical species.

By assuming the term $\partial/\partial z\ (\theta D\ \partial c/\partial z)$ is negligible compared to $\partial(vc)/\partial z$ the equation reduces to $\partial \theta c/\partial t = -\ \partial(vc)/\partial z + S$. This assumption implies that transport due to dispersion in partially saturated soils is negligible compared to the convective transport which occurs. (The earlier conference paper by Hanks, Willardson and Melamed presents a method for handling the source or sink term, S.) This is generally a good assumption.

The model computes the moisture flow (v) and couples the flow with the chemical changes $\partial c/\partial z$ computed in the biological-chemical program to give the salt transport. This technique is the basis for the mixing cell concept.

The chemical exchange model computes the equilibrium chemistry concentrations for calcium, magnesium, gypsum, sodium, bicarbonates, carbonates, chlorides, and sulfates. The nitrogen chemistry including ammonium, nitrates, and urea-nitrogen uses a kinetic instead of an equilibrium approach. The kinetic approach is needed since microbial activity involved in nitrogen transformation occurs over a period of weeks and days instead of minutes and seconds. The equilibrium chemistry for inorganic salts is a good approximation since the reactions describing their chemistry occur in a matter of minutes or seconds in a flow regime which is changing very slowly. A block diagram of the biological-chemical model is given in Fig. 3. A block diagram illustrating the chemical reactions that are considered in one of the subroutines is shown in Fig. 4.

SUMMARY OF MODEL RESULTS

From the calibration of the moisture flow model using infiltration data, water content profiles and storage change data, it was concluded that the water flow could be adequately modeled for the Grand Valley. Several modifications were made to Dutt's original program before the above conclusion could be made.

The functions originally used to calculate $K(\theta)$ and $D(\theta)$ in the model did not permit accurate computation of soil-water flux at water contents close to full saturation for the conditions of this study. A functional relationship developed by Brooks and Corey (1964) was used in the program to calculate hydraulic conductivity [K(θ)]. The function used in the model to calculate soil-water diffusivity [D(θ)] was developed using the relationship developed by Brooks and Corey (1964) for K(θ) and the relationship for the soil-water characteristic developed by Su and Brooks (1975).

The method used to compute the average values of K(θ) and D(θ) required to solve the difference form of Richards equation was also changed. The average value of K(θ) and D(θ) was originally computed using the average water content of the two nodes being considered. The averaging in the flow model was modified so the conductivity is now calculated by using the moisture content at each node and then the calculated conductivities are averaged. The diffusivity is now calculated as an integrated average diffusivity between the water contents at adjacent nodes.

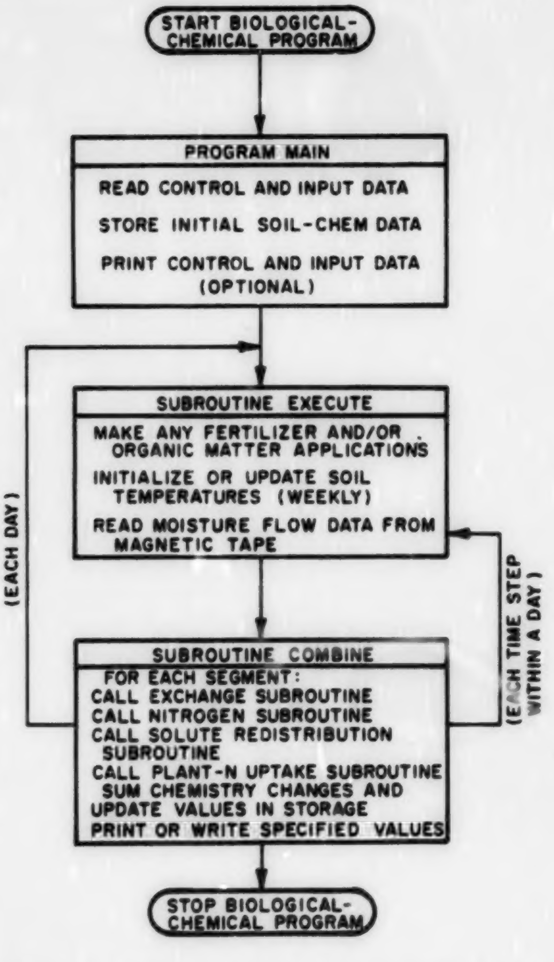
START BIOLOGICAL-CHEMICAL PROGRAM
PROGRAM MAIN
READ CONTROL AND INPUT DATA
STORE INITIAL SOIL-CHEM DATA
PRINT CONTROL AND INPUT DATA (OPTIONAL)
SUBROUTINE EXECUTE
MAKE ANY FERTILIZER AND/OR ORGANIC MATTER APPLICATIONS
INITIALIZE OR UPDATE SOIL TEMPERATURES (WEEKLY)
READ MOISTURE FLOW DATA FROM MAGNETIC TAPE
(EACH DAY)
(EACH TIME STEP WITHIN A DAY)
SUBROUTINE COMBINE
FOR EACH SEGMENT:
CALL EXCHANGE SUBROUTINE
CALL NITROGEN SUBROUTINE
CALL SOLUTE REDISTRIBUTION SUBROUTINE
CALL PLANT-N UPTAKE SUBROUTINE
SUM CHEMISTRY CHANGES AND UPDATE VALUES IN STORAGE
PRINT OR WRITE SPECIFIED VALUES
STOP BIOLOGICAL-CHEMICAL PROGRAM

Figure 3. Generalized block diagram of Biological-Chemical Program.

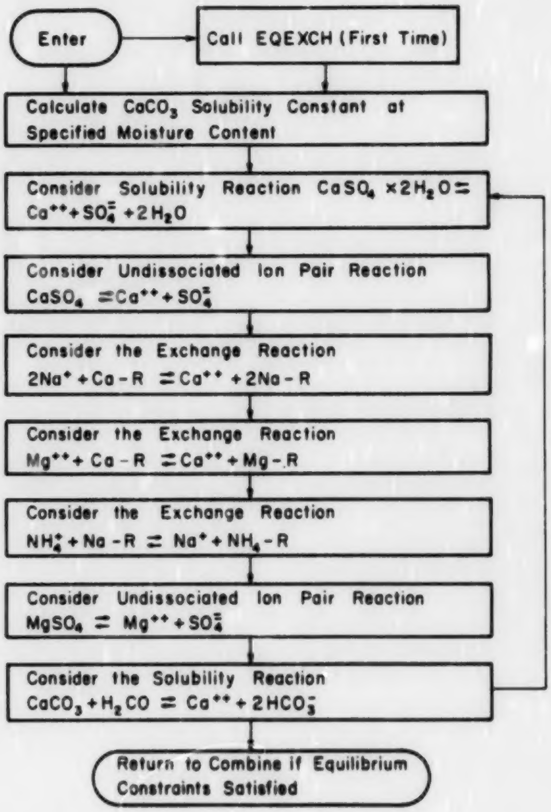
Enter
Call EQEXCH (First Time)
Calculate $CaCO_3$ Solubility Constant at Specified Moisture Content
Consider Solubility Reaction $CaSO_4 \times 2H_2O \rightleftharpoons Ca^{++} + SO_4^{=} + 2H_2O$
Consider Undissociated Ion Pair Reaction $CaSO_4 \rightleftharpoons Ca^{++} + SO_4^{=}$
Consider the Exchange Reaction $2Na^{+} + Ca-R \rightleftharpoons Ca^{++} + 2Na-R$
Consider the Exchange Reaction $Mg^{++} + Ca-R \rightleftharpoons Ca^{++} + Mg-R$
Consider the Exchange Reaction $NH_4^{+} + Na-R \rightleftharpoons Na^{+} + NH_4-R$
Consider Undissociated Ion Pair Reaction $MgSO_4 \rightleftharpoons Mg^{++} + SO_4^{=}$
Consider the Solubility Reaction $CaCO_3 + H_2CO \rightleftharpoons Ca^{++} + 2HCO_3^{-}$
Return to Combine if Equilibrium Constraints Satisfied

Figure 4. Generalized block diagram of subroutine XCHANGE.

After these changes were made, it was possible to predict infiltration, water content distributions and changes in storage that agreed satisfactorily with field measurements. Since the model assumed a homogeneous profile, it was necessary to calibrate the flow model so as to incorporate the variability of field properties into the simulations. The soil water characteristic was calculated as an average from water-content pressure head data gathered through the entire depth of the soil profile in a small area of the test site. This average characteristic was then used to calculate K(θ) and D(θ) in the calibration simulations.

The flow model was calibrated by matching computed infiltration depths and times, water content profiles and storage changes to field measured parameters. The field measured water content profiles were averages of profiles measured at 4 separate locations in the test plot. Only the value of K_s was changed during the calibration, since all other parameters were specified. The calibration was considered complete when the computed values of infiltration duration, storage change and water content profiles were approximately equal to the field measured values. The above procedure is essentially an averaging process which incorporates, to some degree, the field variability of the hydraulic parameters into the flow model.

From comparisons of simulated and field data used in evaluating the chemistry component of Dutt's model, it was concluded that TDS concentrations were adequately modeled but that individual ionic species concentrations were not. The simulations used to compare computed and field chemistry data were made using field data for initial and boundary conditions in both the chemistry and flow models. Field data on the chemical composition of the soil solution extracted at a depth of 1.1 meters for a 30 day period was used to compare with calculated salt concentrations.

Comparisons of calculated and measured data indicate that the $CaSO_4$ - $CaCO_3$ - $Ca(HCO_3)_2$ system is not adequately modeled for the soils in the Grand Valley. The model computed Ca^{++} concentrations at a depth of 1.1 meters that were greater than theoretical maximum values expected for this soil system. A study of the $CaSO_4$ - $CaCO_3$ - $Ca(HCO_3)_2$ equilibrium equations indicated that the solubility product of $Ca(HCO_3)_2$ calculated using ion activities was incorrect. The solubility of calcium bicarbonate, $Ca(HCO_3)_2$, was then calculated based on the partial pressure of carbon dioxide. A reasonably good agreement between computed and measured TDS concentration was obtained using a value of 7 matm for the partial pressure of carbon dioxide in the simulations.

Data for single growing season simulations using 7 and 14 day irrigation schedules and 2%, 5%, 20%, and 40% leaching increments (Figure 5), coupled with data from a 6 year simulation using a 14 day irrigation schedule and 20% leaching increment (Table 1, year 1 and 6) indicate that the salt concentration of the leachate is independent of the volume of leachate. TDS profiles calculated at the beginning and end of the six-year simulation (Figure 6) show the concentration of salt in the profile below a depth of 122 cm, which is the bottom of the root zone in the simulation, to be relatively constant. Apparently, this zone acts as a buffer and causes the salt concentration in the leachate at the bottom of the profile to be relatively constant.

In summary, the salt loading due to irrigation return flow can be calculated from a knowledge of the water balance in the system. Reductions, therefore, in salt loading would be directly proportional to changes which reduced the volume of return flow. (Similar results were obtained by Hanks, Willardson and Melamed as reported earlier in these proceedings.) Estimating salt loading on a valley-wide scale would require a knowledge of the volume of the return flow and the concentration of salts in the flows. The latter can be predicted from the model used in this study if measured values are not available.

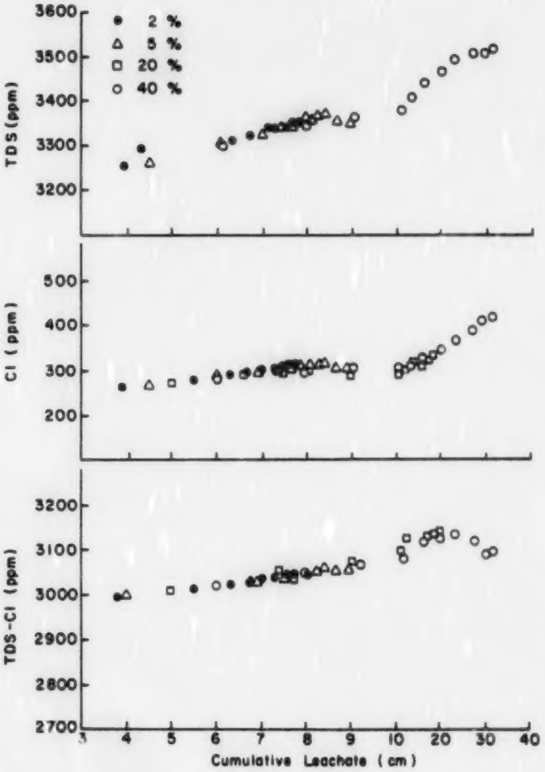

Figure 5. TDS and chloride concentrations as a function of cumulative leachate at a depth of 2.1 m calculated by hypothetical simulations using a 14-day irrigation interval.

TABLE 1

TDS concentrations and chloride concentrations in cumulative leachate at 2.13 m for 6 year hypothetical simulation using 14 day irrigation schedule and 20% leaching increment.

Julian Date	*Cumulative Infiltration (cm)*	*Cumulative Leachate (cm)*	*Cl ppm*	*TDS ppm*	*TDS-Cl ppm*
		Year 1 of 6			
157	8.33	5.02	269	3276	3007
171	11.45	6.70	290	3318	3028
185	16.46	7.48	298	3336	3038
199	23.50	8.05	302	3352	3050
213	31.64	8.92	297	3352	3055
227	40.55	10.11	299	3365	3066
241	51.25	11.93	302	3391	3089
255	60.49	12.86	317	3416	3099
269	68.36	13.66	323	3432	3109
283	75.11	14.31	327	3444	3117
293	80.55	14.75	327	3444	3117
		Year 6 of 6			
157	409	71.85	446	3479	3033
171	413	72.60	411	3435	3024
185	418	73.29	413	3439	3026
199	425	73.85	412	3438	3026
213	433	74.71	398	3422	3024
227	442	75.89	390	3414	3024
241	452	77.49	382	3406	3024
255	462	78.69	391	3415	3024
269	470	79.45	392	3418	3026
283	476	80.10	392	3421	3029
293	482	80.55	390	3418	3028

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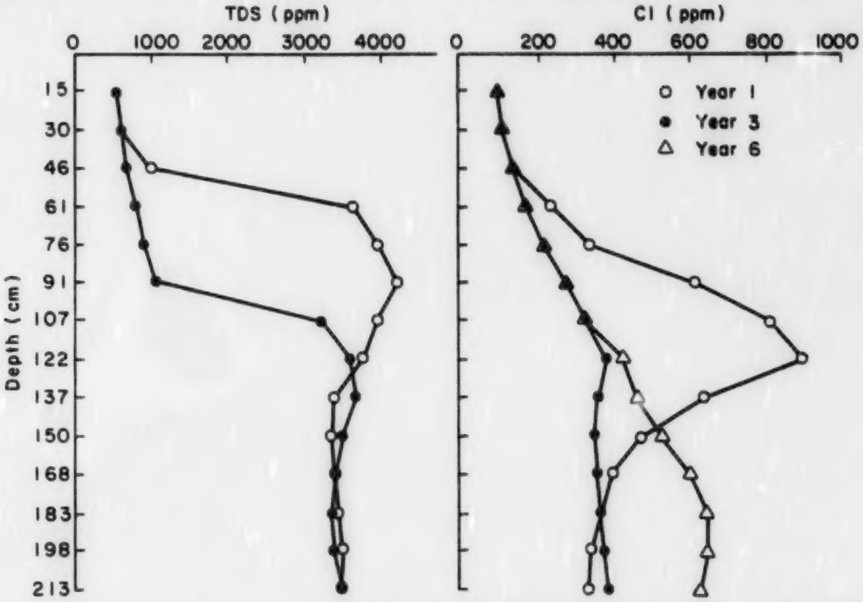

Figure 6. TDS and chloride concentration profiles at day 293 calculated by a 6-year hypothetical simulation using 20% leaching increment and 14-day irrigation interval.

Evaluating Appropriate Technologies for Salinity Control in Grand Valley

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ABSTRACT

A summary of the results of applied research on salinity control of irrigation return flows in the Grand Valley of Colorado is presented for the period of 1969 to 1976. Salinity and economic impacts are described for the Grand Valley Salinity Control Demonstration Area which contains approximately 1600 hectares and involves most of the local irrigation entities in the valley. During the eight years of the demonstration project, 12.2 km of canals were lined, 26.54 km of laterals were lined, 16.4 km of drainage tile was installed, a wide variety of on-farm improvements were constructed, and an irrigation scheduling program was implemented. The total value of the constructed improvements in the demonstration area was almost $750,000.

INTRODUCTION

In 1967, the irrigation companies of Colorado's Grand Valley became concerned with the potential financial burden which could be placed upon the valley's water users by salinity damages downstream, especially if they were forced to comply with salinity control measures at their expense. Consequently, they began efforts to initiate action based on the concept that abatement of the salinity problem would have state, regional, national and international benefits.

The irrigation companies formed a cooperative organization called the Grand Valley Water Purification Project, Inc. (later called Grand Valley Canal Systems, Inc.), and petitioned the Federal Water Quality Administration for matching funds for demonstrating canal lining as a salinity control measure. This money was forthcoming, and in 1968 the Agricultural Engineering Department of Colorado State University contracted to do the technical evaluation regarding the effectiveness of canal lining for reducing the Grand Valley's salt load contribution to the Colorado River.

As time progressed, additional studies were initiated to determine the potential benefits of other technologies such as irrigation scheduling, drainage, and lateral improvements for controlling salinity in the Grand Valley. A summary of the results of these various investigations is reported herein. A map illustrating the study area and the various investigations is shown in Figure 1.

CHANNEL LINING

The results of the 1969 channel lining studies indicated that canal and lateral lining in the study area reduced salt inflows to the Colorado River by about 4,000 metric tons annually (Skogerboe and Walker, 1972). The bulk of this reduction is attributable to the canal linings, but clearly indicated is the greater importance of lateral linings. The length of laterals (600 km), plus the farm head ditches (1640 km), is about eight times greater than the length of canals (286 km). The economic benefits to the Lower Basin water users alone exceed the costs ($350,000 construction plus $70,000 administration) of this project. Consequently, it is justifiable to conclude that conveyance lining in areas such as the Grand Valley, where salt loadings reach 18 metric tons or more per hectare, are a feasible salinity control measure. The local benefits accrued from reduced maintenance, improved land

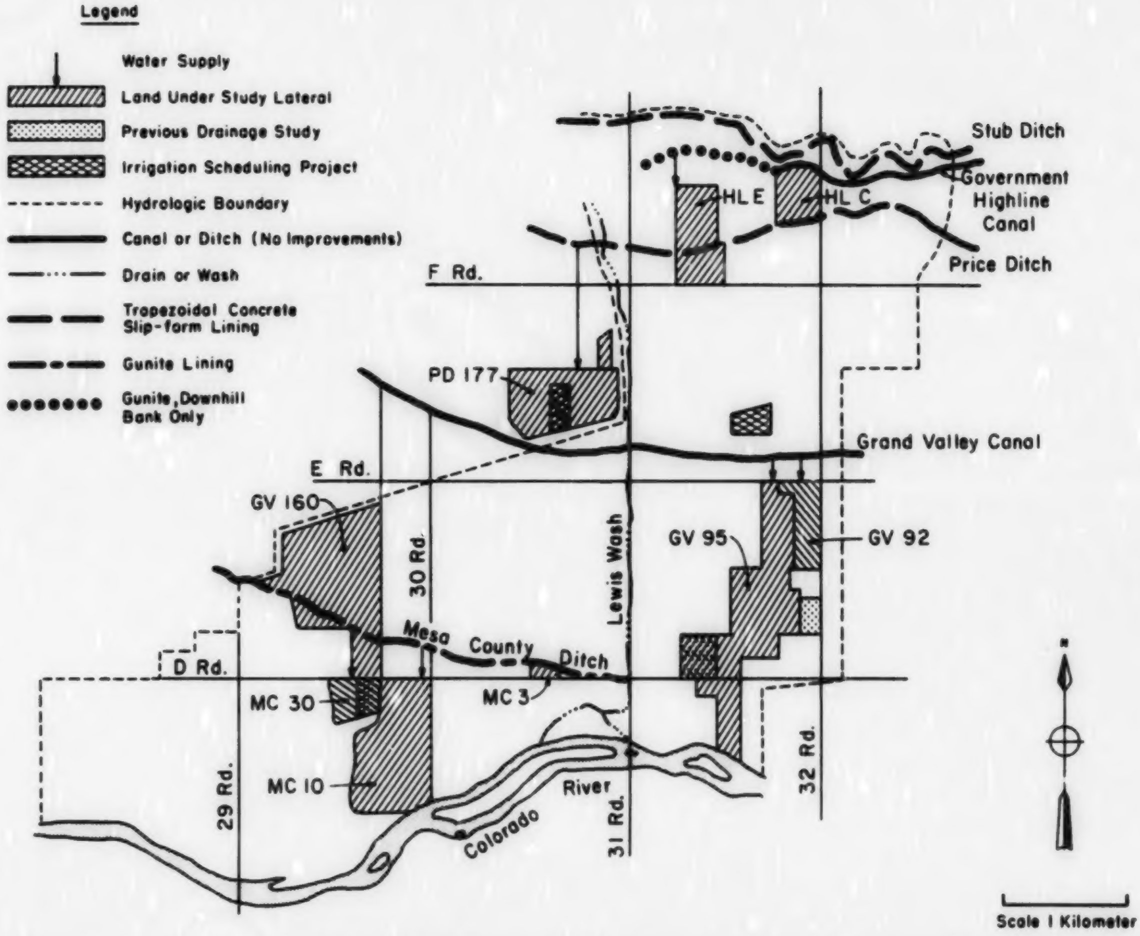

Legend
Water Supply
Land Under Study Lateral
Previous Drainage Study
Irrigation Scheduling Project
Hydrologic Boundary
Canal or Ditch (No Improvements)
Drain or Wash
Tropezoidal Concrete Slip-form Lining
Gunite Lining
Gunite, Downhill Bank Only
Stub Ditch
Government Highline Canal
Price Ditch
HL E
HL C
F Rd.
PD 177
Grand Valley Canal
E Rd.
GV 160
30 Rd.
Lewis Wash
GV 95
GV 92
Mesa County Ditch
D Rd.
MC 30
MC 3
MC 10
29 Rd.
River
Colorado
31 Rd.
32 Rd.
N
Scale 1 Kilometer

Figure 1. Grand Valley Salinity Control Demonstration Area showing the locations of the various investigations conducted from 1969 to 1976.

value, and other factors add to the feasibility of conveyance linings as a salinity management alternative.

The first and most important consideration in improving farm water use is control. Implied in this realization is the requirement of sound water measurement at the farm turnout and again at critical division points below the turnout. This would necessitate a considerable rehabilitation of both the canal and lateral system and the implementation of a "call period" to allow canal operators more time for flexible water handling. In addition, it is important that the canal companies extend their control of the water below the canal turnout structure to include key division points within the lateral system to insure equitable allocation of water among users.

IRRIGATION SCHEDULING

The irrigation of agricultural lands in the Colorado River Basin is a significant cause of the salinity concentrations encountered in the Colorado River. Emphasis towards stemming further salinity increases has logically centered upon improving the quality of irrigation return flows. This emphasis, especially in the high salt contributing areas like the Grand Valley in western Colorado, focuses upon reducing the flows which pass through the saline soils and aquifers, thereby reducing the salt pickup which occurs by dissolution. Since a major fraction of the water percolating through local soils in this manner comes from over-irrigation, measures aimed at improving irrigation efficiencies have a high potential for controlling salinity. Among the methods for achieving higher water use efficiencies on the farm, "scientific" irrigation scheduling is one of the most important (Skogerboe, Walker, Taylor and Bennett, 1974).

Irrigation scheduling consists of two primary components: crop evapotranspiration and available root zone soil moisture. Evapotranspiration is calculated by using climatic data. The other major category of required data pertains to soil characteristics. First of all, field capacity and permanent wilting point for the particular soils in any field must be determined. More importantly, infiltration characteristics of the soils must be measured. Only by knowing how soil intake rates change with time during a single irrigation, as well as throughout the irrigation season, can meaningful predictions be made of: (a) the proper quantity of water which should be delivered at the farm inlet for each irrigation; and (b) the effect of modifying deep percolation losses. With good climatic data and meaningful soils data, accurate predictions for the next irrigation date and the quantity of irrigation water to be applied can be made. In order to enable the irrigator to apply the proper quantity of water, a flow measurement structure is absolutely required at the farm inlet.

The results of this demonstration project indicated that irrigation scheduling programs have a limited effectiveness for controlling salinity in the Grand Valley under existing conditions. Excessive water supplies, the necessity for rehabilitating the irrigation system (particularly the laterals), and local resistance to change preclude the proper management of water applied during successive irrigations. To overcome these limitations, irrigation scheduling must be accompanied by flow measurement at all the major lateral division points and farm inlets. In addition, it is necessary for the canal companies and irrigation districts to assume an expanded role in delivery of the water. Also, some problems have been encountered involving poor communication between farmer and scheduler and certain deficiencies in the USBR computerized scheduling program which was used in this study dealing with evapotranspiration and soil moisture predictions. Correcting these conditions is easily rectified and will make irrigation scheduling much more effective and acceptable locally.

Water budgets from which the study results were generated were obtained from intensive investigation on two local farms. The selection of the two study farms was intended to be representative of conditions valley-wide. Analysis of the budgets reveal that approximately 50 percent of the water applied to the fields came during the April and May period when less than 20 percent of the field evapotranspiration potential had been experienced. Salt pickup estimates during this early part of the season amounted to about 60 percent of the annual total for each field. Another indication of the importance of early season water management is presented in an analysis of irrigation efficiencies. As the season progressed, the soils became less permeable and the crop water use increased, causing marked improvements in irrigation efficiency. Thus, if irrigation scheduling is employed in its optimal format, salt pickup from the two fields can be reduced as much as 50 percent or more.

The results of this demonstration project show that irrigation scheduling is a necessary, but not sufficient tool for achieving improved irrigation efficiencies. The real strides in reducing the salt pickup caused by over-irrigation will come from the employment of scientific irrigation scheduling in conjunction with improved on-farm irrigation practices.

DRAINAGE

Drainage investigations in the Grand Valley began shortly after the turn of this century when local orchards began failing due to high saline water tables. Studies showed the soils to be not only saline but also of low permeability. At the time, the future development of the Bureau of Reclamation's "Grand Valley Project" loomed as a severe threat to the low lying lands between it and the Colorado River. As an answer to these apparent drainage needs, the solutions were clearly set forth but never fully implemented. Rather, a local drainage district was formed to construct open ditch interceptor drains and some buried tile to correct trouble spots. All of these efforts barely contained the rise in water tables, and today more than fifty years later, the local conditions remain essentially unchanged.

This study was undertaken with the history of local drainage well in mind, but for a different purpose, the skimming of water from the top of the water table before it reaches chemical equilibrium with the highly saline soils and aquifers. A farm owned by Mr. Bob Wareham was used in the study to demonstrate the skimming effect by installing field relief drains on 12.2-meter centers. The field had been under poor irrigation management for several years, so the results are not immediately discernable. However, analysis of water quality throughout the study area indicated that effective relief drainage would intercept flows with a salinity concentration as much as 3000 mg/l lower than existing groundwater concentrations.

In viewing the results of this study, it is obvious that field drainage is a curative rather than preventive measure. High costs of such programs illustrate the need of first minimizing the flows passing through the root zone or seeping from canals and laterals. The small amount of water entering the groundwater could then be effectively removed by drainage systems located at selected locations. Thus, field drainage as it pertains to objectives of salinity control is a remedy which must be considered but will probably not be implemented until the last stages of salinity control in the valley (Skogerboe, Walker, Bennett, Ayars and Taylor, 1974).

LATERAL IMPROVEMENTS

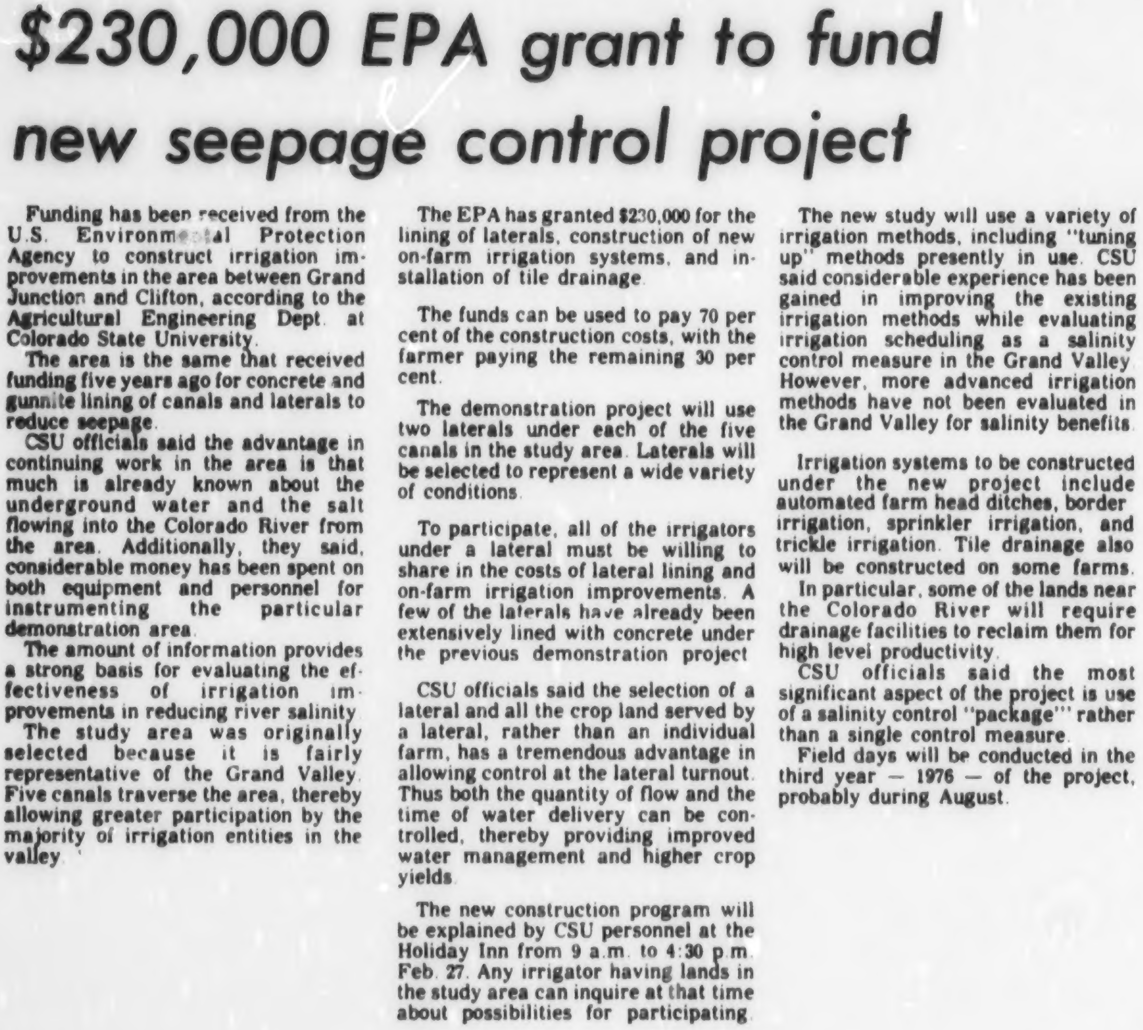
Since this study involved the selection of several laterals in which the irrigators to be served would participate by contributing to the construction costs, the total cooperation of these people was imperative. By first publicly advertising the project, and then personally contacting one or more parties who seemed most interested, about eleven potential groups in the project area were identified. After the people had discussed the matter among themselves, project personnel arranged meetings where specific details of the project were outlined and questions answered. Since the average farm size in the area is about 2 to 6 hectares (5 to 15 acres), the number of people involved could have been as high as one hundred. In actuality, there were 89 persons involved. Interestingly, problems anticipated in coordinating such a large group did not materialize.

The first step in the lateral selection process began when an announcement of the project, along with a project location map, was placed in the local newspaper (Figure 2). The article stated the funding availability, its purposes, conditions for qualifying, and the availability of project representatives at an upcoming question and answer session. Prior to this "open house", the writers had envisioned the possibility of a long period of door-to-door field contact. However, forty individuals representing ten laterals within the demonstration area attended the session, and further contact was not necessary. The overwhelming response at the open house resulted in considerable time savings and undoubtedly ranks as one of the most important events leading to the project's success.

At the open house, each inquirer was advised that the best action at that time would be to contact others on the lateral, briefly explain the project objectives, and enlist support. Contact with the individuals who came to the open house was re-established several weeks later, and meetings with project personnel were scheduled. With the exception of two cases, the meetings were unqualified successes in gaining the acceptance of the people involved. Lateral groups desiring the project's help were told final site selection would not be made until the fall or winter of 1974-75 so that each lateral could be evaluated for its usefulness in satisfying the project objectives. Also, this time was used by irrigators to finalize their own willingness to be included in the project and to reach agreement among themselves concerning such matters as cost sharing and the desirable operating characteristics of the improved irrigation systems.

The project was established on the basis that the project would pay 70 percent and the participants 30 percent of the total construction costs, not including engineering or administration. The 30 percent matching requirement could be paid in cash or by equal value arrangements such as direct labor, equipment rentals, land leveling costs, or through the voluntary assistance of local organizations such as the Grand Junction Drainage District.

As more was learned about the various lateral systems and the attitudes of the irrigators, it was necessary to continually reevaluate each lateral in terms of project objectives. In addition, throughout the first year, project personnel received numerous requests (at least 2 or 3 per week during the summer months of 1974) from other interested landowners within the project area. In fact, requests for assistance are still being received after completion of the project.



$230,000 EPA grant to fund new seepage control project

Funding has been received from the U.S. Environmental Protection Agency to construct irrigation improvements in the area between Grand Junction and Clifton, according to the Agricultural Engineering Dept. at Colorado State University.

The area is the same that received funding five years ago for concrete and gunnite lining of canals and laterals to reduce seepage.

CSU officials said the advantage in continuing work in the area is that much is already known about the underground water and the salt flowing into the Colorado River from the area. Additionally, they said, considerable money has been spent on both equipment and personnel for instrumenting the particular demonstration area.

The amount of information provides a strong basis for evaluating the effectiveness of irrigation improvements in reducing river salinity.

The study area was originally selected because it is fairly representative of the Grand Valley. Five canals traverse the area, thereby allowing greater participation by the majority of irrigation entities in the valley.

The EPA has granted $230,000 for the lining of laterals, construction of new on-farm irrigation systems, and installation of tile drainage.

The funds can be used to pay 70 per cent of the construction costs, with the farmer paying the remaining 30 per cent.

The demonstration project will use two laterals under each of the five canals in the study area. Laterals will be selected to represent a wide variety of conditions.

To participate, all of the irrigators under a lateral must be willing to share in the costs of lateral lining and on-farm irrigation improvements. A few of the laterals have already been extensively lined with concrete under the previous demonstration project.

CSU officials said the selection of a lateral and all the crop land served by a lateral, rather than an individual farm, has a tremendous advantage in allowing control at the lateral turnout. Thus both the quantity of flow and the time of water delivery can be controlled, thereby providing improved water management and higher crop yields.

The new construction program will be explained by CSU personnel at the Holiday Inn from 9 a.m. to 4:30 p.m. Feb. 27. Any irrigator having lands in the study area can inquire at that time about possibilities for participating.

The new study will use a variety of irrigation methods, including "tuning up" methods presently in use. CSU said considerable experience has been gained in improving the existing irrigation methods while evaluating irrigation scheduling as a salinity control measure in the Grand Valley. However, more advanced irrigation methods have not been evaluated in the Grand Valley for salinity benefits.

Irrigation systems to be constructed under the new project include automated farm head ditches, border irrigation, sprinkler irrigation, and trickle irrigation. Tile drainage also will be constructed on some farms.

In particular, some of the lands near the Colorado River will require drainage facilities to reclaim them for high level productivity.

CSU officials said the most significant aspect of the project is use of a salinity control "package"' rather than a single control measure.

Field days will be conducted in the third year — 1976 — of the project, probably during August.

Figure 2. Announcement of grant award in *Daily Sentinel* (Grand Junction, Colorado).

The selection of a lateral as the subsystem, rather than an individual farm, has the advantage of maintaining control at the lateral turnout. In this way, both the quantity of flow and the time of water delivery can be controlled, thereby facilitating improved water management throughout the system. The lands selected demonstrated a wide variety of irrigation and drainage problems which provided a representative cross section of the valley's irrigated lands. With the available knowledge regarding the study area, a lateral and its associated lands could be used as a logical subsystem for evaluating the salinity reduction in the Colorado River resulting from the implementation of a salinity control technology package.

The laterals selected were evaluated on the basis of four broad criterion:

1. Participation from all the water users on lands served by the lateral;
2. The degree of participation in all three phases of the project (pre-evaluation,

construction, and post-evaluation) covering the project's three-year period;

3. The type and extent of irrigation and drainage problems represented, and the different solutions and alternatives which were agreeable and economically advantageous to the landowners; and
4. The analysis of the least cost expenditures, demonstration value to other farmers, and maximum production of research results in order to realize project objectives.

One hundred precent participation was required to accomplish one of the major goals of the project:to demonstrate the effectiveness of a "package" of technological improvements on a broad scale for purposes of salinity control. This was not a problem in any way during the project.

Numerous lateral group meetings and individual discussions with irrigators were used to evaluate, as objectively as possible, the anticipated degree of voluntary participation in the project's three phases, as well as their willingness to change existing irrigation practices and methods. This was very critical since many of the proposed lateral systems might be designed in such a way that a return to old methods and practices would be practically impossible, and proposed management methods might be mandatory for continued operation of the system. The results and implications were fully explained to all the participants before any final decisions were mutually agreed upon.

The type of physical problems and the extent of these problems were carefully examined by project personnel to insure that unnecessary duplication did not occur and that as many different problems as possible could be treated by a variety of technologies. The long range objectives of agricultural salinity control in the Grand Valley, and the Colorado River Basin, were also taken into account in choosing the types of problems to be studied.

The composition of various existing salinity control technologies were carefully matched to achieve a maximum effect on each lateral subsystem. Planned treatments included sprinkler irrigation, drip (trickle) irrigation, concrete lateral linings, concrete head ditches, gated pipe, automated cut-back irrigation, land shaping and clearing, flow measurement, tailwater removal systems, buried PVC plastic irrigation pipelines, field drainage, irrigation scheduling, and various improved water management practices for each subsystem.

Once the selected laterals were identified by their special problems, the alternative solutions for alleviating these problems were presented to the landowners and a proposed course of action was planned in complete accordance with the wishes of all parties. Then, project personnel analyzed the costs of various alternatives and prepared basic quantity take-offs and preliminary cost estimates. Further meetings were held with the water users under each lateral and final plans were mutually adopted.

General Considerations in Design and Construction

All of the improvements were organized into a logical experimental design in order to effectively evaluate the objectives of the project, and an overall design philosophy was formulated to govern the designs of improvements within the lateral subsystems.

The first major consideration was the placement of flow measurement devices in each lateral subsystem. These measurement devices were placed immediately below all the lateral headgates and measurement structures were placed at all flow divisions and after each farm delivery point on the main delivery system. Also, all measurement devices can be read directly without the use of tables or calculations. To accomplish this, propeller meters read directly in cubic feet per second (cfs), and special enameled metal staff gauges were designed and manufactured for all the Cutthroat flumes which read directly in cfs and Colorado miner's inches. Two sizes of Cutthroat flumes were standardized throughout the project: 1) a 20.3-cm throat width by 91-cm length (8-inch throat width by 3-foot length), and 2) 7.6-cm throat width by 91-cm in length (3-inch throat width by 3-foot length).

Another consideration was the grade for all pipelines and concrete ditches would be governed by the slope of land surfaces when possible. This reduced costs considerably because it eliminated the necessity of many costly drop structures and energy dissipation facilities. Improvements followed old channels where possible and an attempt was made to consolidate ditches and laterals to minimize duplication of facilities. Also, efforts were made to consolidate land where possible under each lateral in order to maximize the usefulness of the improvements.

Anytime a lateral passed or went through a subdivision or other urban area, the water was conveyed in a closed conduit for health and safety reasons, for the aesthetics of eliminating an open ditch, and to minimize debris problems caused by children playing in the ditch.

Under roadways and access routes, the PVC plastic irrigation pipes were encased with concrete pipe. Anytime a corrugated metal pipe (CMP) culvert was replaced or relocated, it was replaced with a sulfate resistant concrete pipe. The concrete pipe was about one-half the material cost of CMP, but the initial installation costs were higher. However, in the highly saline soil conditions of the Grand Valley, the concrete would be expected to outlast the CMP by at least 20 years.

When water was taken from a lateral to irrigate landscapes in a subdivision, where possible the subdivision water was separated from the agricultural water because the methods of operation are so different as to be incompatible with one another.

Construction of Lateral Improvements

Construction was completed in three stages during the fall of 1974, the spring of 1975, and the fall of 1975 with the majority of the construction completed by the start of the 1975 irrigation season. Based upon the designs and a complete list of materials, contractor and materials specifications were prepared in the fall of 1974. A summary of the construction by lateral and the value of the improvements is presented in Table 1. An illustrative summary of the mixing of technologies utilized on a single lateral (MC 10) to maximize the research and demonstration effectiveness is presented in Figure 3.

Irrigator Response to the Project

Several of the lateral groups elected to do much of the construction work themselves and were thus very involved in day-to-day operations. On other laterals, where the construction

TABLE 1

Summary of project improvements on lateral subsystems.

	LATERAL									
Types of Improvements[6]	*HL C (13.1 h)*	*HL E (35.9 h)*	*PD 177 (27.8 h)*	*GV 92 (24.3 h)*	*GV 96 (79.1 h)*	*GV 160 (78.7 h)*	*MC 3 (3.7 h)*	*MC 10 (54.0 h)*	*MC 30 (14.1 h)*	*TOTAL (330.7 h)*
Concrete Ditches (m)		[1]	230[1]	189	2,789	1,898	157	2,723[1]	1,040	9,026
Buried Plastic Pipelines										
Gravity systems (m)		792	2,051	817	2,312	2,573[5]		1,054	195	9,794
Pressurized systems (m)		3,274			378					3,652
Gated Pipe (m)			207		583			564	122	1,476
Drip Irrigation (h)			2.2							2.2
Overhead Sprinklers (h)		5.2								5.2
Sideroll Sprinklers (h)					4.0					4.0
Drainage Works (h)	2.2[4]	8.0[4]			6.5	11.5	2.5	6.1	[2]	36.8
Plastic Drainage Tile (m)					2,667	3,496	1,958	4,958		13,079
Concrete Drainage Tile (m)	244	198								442
Flow Measurement (No.)	(3)	(4)	(14)	(3)	(25)	(27)	(3)	(18)	(5)	(102 TOTAL)[7]
Cutthroat Flumes (No.)		2	3	2	18	26	2	14	3	70
90° V-Notch Weirs (No.)	1		1		1					3
Parshall Flumes[3] (No.)	2		3		1			2	2	10
12" Propellor Meters (No.)			1		1			1		3
10" Propellor Meters (No.)			1		2	1				4
8" Propellor Meters (No.)		1	3		1			1		6
Other Meters (No.)		1	2		1					4
Metering Headgates (No.)				1			1			2
Debris Removal Equipment (No.)		1	1		1					3
Land Shaping, etc. (h)					24.3			11.3		35.6
Irrigated Hectares (Possible)	11.5	34.2	22.7	20.4	69.8	53.5	3.0	44.2	13.8	275.3
Total Value	$4,860.	$30,760.	$43,970.	$13,600.	$104,790.	$84,680.	$18,440.	$68,540.	$8,690.	$378,330.
Value/Hectare	370.	860.	1,580.	560.	1,320.	1,080.	4,980.	1,270.	620.	1,140.
Value/Irrigated Hectare	420.	900.	1,940.	670.	1,500.	1,580.	6,150.	1,550.	630.	1,370.

[1] These laterals were part of the earlier canal and lateral lining study and contain approximately an additional 1390 meters of concrete ditches and 790 meters of concrete pipe not included above.

[2] This lateral was part of a previous drainage study and contains an additional 3353 meters of plastic drainage tile on 4 hectares not included above.

[3] These flumes were removed at the end of the project since they measured field runoff.

[4] Interceptor drains, concrete tile. HL C tiled a large open drain, HL E is a new drain.

[5] Includes 99 meters of 25 and 38 cm diameter concrete pipe.

[6] m = meters, h = hectares, No. = number.

[7] This total flow measurement count does not include the flow measurement structures used in monitoring the hydrology for the whole demonstration area.

was facilitated by contractors, some irrigators were out every day asking questions and making suggestions on construction procedures and improvement of system performance. The willingness of the irrigators to become involved in the construction is desirable because they develop a much better understanding of the system design, operation, and maintenance. However, on one lateral (GV 95) the fact that the irrigators opted to pay for the construction contributed to many problems encountered later in the project. Due to the lack of daily involvement, many of these irrigators lacked a complete understanding of the system and its operation. Ultimately, this caused some conflicts which should not have occurred. However, with considerable time and effort, these conflicts have been resolved.

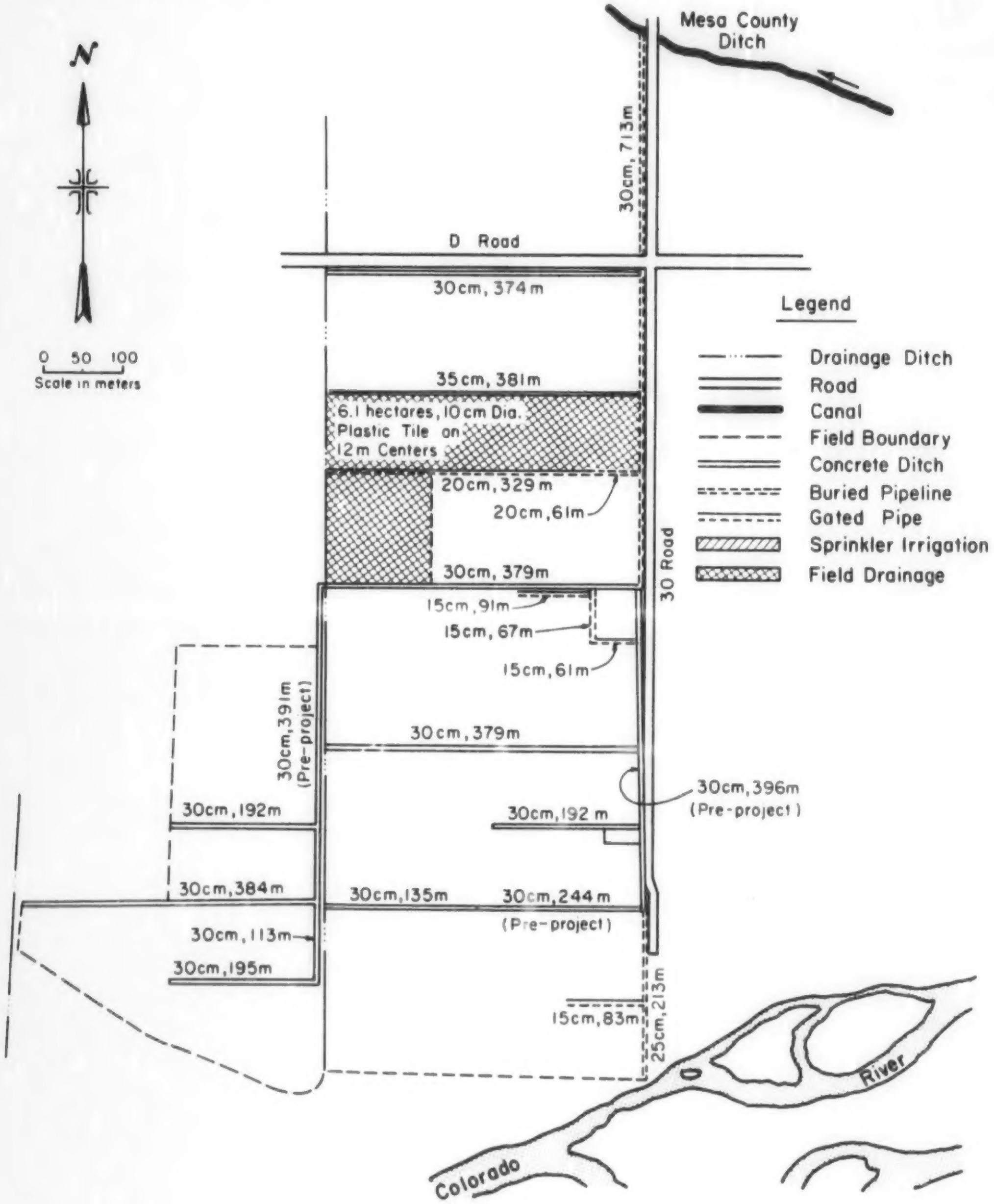

N
0 50 100
Scale in meters
Mesa County Ditch
30cm, 713m
D Road
30cm, 374m
35cm, 381m
6.1 hectares, 10cm Dia. Plastic Tile on 12m Centers
20cm, 329m
20cm, 61m
30cm, 379m
30 Road
15cm, 91m
15cm, 67m
15cm, 61m
30cm, 391m (Pre-project)
30cm, 379m
30cm, 396m (Pre-project)
30cm, 192m
30cm, 192 m
30cm, 384m
30cm, 135m
30cm, 244 m (Pre-project)
30cm, 113m
30cm, 195m
15cm, 83m
25cm, 213m
Colorado River
Legend
Drainage Ditch
Road
Canal
Field Boundary
Concrete Ditch
Buried Pipeline
Gated Pipe
Sprinkler Irrigation
Field Drainage

Figure 3. Map of lateral and on-farm improvements under MC 10 lateral system.

The construction work was very personally gratifying in many ways. Many people went out of their way to help and assist others on the laterals. For example, on the Price Ditch 177 lateral subsystem, several people from the subdivision on the end of the lateral assisted in laying pipeline for agricultural users, and two of these people donated equipment for construction work on the project.

In another case, on the Grand Valley Canal 160 lateral subsystem, people without water rights in the lateral assisted their neighbors in pipeline construction. Also, on this lateral, an 8-inch diameter plastic pipeline replaced more than a quarter mile of unlined ditches to one farm. The pipeline was completely installed by neighbors of of the family because of head of the household had suffered a heart attack.

On the Mesa County 10 lateral subsystem, people donated their own equipment for the construction of the pipeline system. One elderly gentleman with just a few acres had his sons come and do his share of the work on the pipe installation.

These examples illustrate occurances on many of the laterals where community effort was require to complete the work.

Cooperation Among Irrigators

In general, mutual cooperation between irrigators on the project has improved quite noticeably since construction began, particularly where participants did much of the installation themselves. The new systems have reduced cases of antagonism due to ditch maintenance or inequitable water allocation. For instance, under the new systems, yearly maintenance is reduced because of concrete lined laterals or the use of pipelines. Also, ineffective or outdated division structures were replaced with new structures containing flow measuring devices, removing many areas of previous discontent.

Prior to the project some of the laterals had previously developed water rotation systems. The construction of these new systems greatly facilitated the ease and speed of water delivery, and contributed to the development of a new awareness of water rights through water measurement. Consequently, rotations have become more widely accepted as a beneficial practice.

The construction process also helped the irrigators become much more aware of water delivery problems. They now have more consideration for their neighbors. There is more communication between irrigators in determining the timing and amount of deliveries because of increased emphasis upon improved water management practices.

Participation by Local Organizations

There was a large amount of participation by local organizations, which substantially contributed to the project's success. The largest degree of participation was by the Grand Junction Drainage District, closely followed by the Mesa County Road Department and the local irrigation companies.

The Grand Junction Drainage District, through their standard drain installation agreement, installed almost 13 kilometers (8 miles) of drainage tile for this project. The Mesa County Road Department installed and replaced numerous road crossings and culverts and provided some backfill for deeply eroded areas near county roads. The Grand Valley Irrigation Company and the Grand Valley Water Users Association suggested ways of modifying lateral operational procedures and replaced worn out headgates, and they agreed to let project personnel manage the operation of headgates on the selected laterals. This was a very important component of the project's success in demonstrating improved water management practices.

Meetings were also held with the Grand Valley Rural Electric Association, the Mesa County Tax Assessor, Mountain Bell Telephone Company, local natural gas companies, bank officials, attorneys, and water and sewer district officials to obtain necessary information, cooperation, and other assistance on construction easements, utility locations and relocations, possible legal problems, and various financial aspects of the project.

Almost 610 meters (2000 linear feet) of 30-cm (12-inch) diameter plastic irrigation pipeline was installed, free of charge, by a local construction company. They installed the pipe because lateral GV 160 crossed about 122 meters (400 feet) of land belonging to the company. In order to make the area more usable for their construction related activities, the contractor offered to install the pipe at no charge. The project supplied all the materials.

In general, the support given by local business and organizations was overwhelming

and undoubtedly a large reason for the attainment of the project's objectives. The *Grand Junction Daily Sentinel*, a local daily newspaper, was also of great assistance in promoting project goals and reporting on project activities and developments.

Summary of Improvements and Costs

In summary, the improvements completed in the project area since 1969 as part of the demonstration of salinity control include: 12.2 km (7.6 miles) of large canal linings, 26.59 km (16.51 miles) of lateral linings, 16432 meters (53,913 feet) of perforated field drainage tile, construction of a wide variety of on-farm improvements, and an irrigation scheduling program. The costs of the various improvements, which totaled almost $750,000, are listed in Table 2.

The total value of the lateral improvements (since 1974) for the project is $378,330, installed on 330.7 hectares for an average cost of $1140 per hectare ($460 per acre).

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TABLE 2

Construction program of previous improvements in the Grand Valley Salinity Control Demonstration Project.

Map Designation	*Company Name Canal Name*	*Type of Improvement*	*Length*		*Perimeter*		*Area*		*Unit Cost*		*Miscellaneous Costs*	*Total Cost*
			(mi.)	*(km)*	*(ft.)*	*(m)*	*(yd²)*	*(m²)*	*($/yd²)*	*($/m²)*	*($)*	*($)*
Area I (Demonstration Area)												
A	Grand Valley Irrigation Co. Mesa County Canal	Gunite Lining	2.2	3.5	14	4.3	17,500	14,632	3.25	3.89	2,100.00	58,975.00
B	Palisades Irrigation Dist. Price Ditch	Slip Form Lining	1.9	3.1	15	4.6	16,720	13,980	3.25	3.89	2,900.00	56,240.00
C	Grand Valley Waters Users Assn. Gov't Highline Canal	Gunite Lining	1.0	1.6	15+	4.6	8,800	7,358	3.50	4.19	5,800.00	36,600.00
D	Mesa County Irrigation Co. Stub Ditch	Slip Form Lining	2.5	4.0	10	3.1	14,700	12,290	3.25	3.89	3,500.00	51,275.00
E	Grand Junction Drainage Co.											
	Open Drains	Slip Form Lining										4,000.00
	Closed Drains	Tile										16,000.00
	Laterals	Slip Form Lining	4.83	7.77								110,815.00
Area II												
F	Grand Valley Irrigation Co. Grand Valley Canal	Gunite Lining	0.15	0.24	15+	4.6	1,320	1,104	3.50	4.19	4,000.00	8,620.00
Area III												
G	Redlands Water and Power	Slip Form Lining	0.5	0.8	12	3.7	3,500	2,926	3.25	3.89	1,600.00	11,475.00
SUBTOTAL												354,000.00
			(ft)	(m)	(in.)	(cm)	(ac)	(ha)	($/ac)	($/ha)		
Drainage Costs			11,000	3,353	4‡	10.2‡	10	4.1	1,694.00	4,185.82	0.00	16,940.00
SUBTOTAL												$370,940.00
Lateral Improvements												378,330.00
TOTAL VALUE of direct benefits to the Grand Valley												$749,270.00

*Costs of pre-construction and post-construction ponding tests above amounts in CSU contract, plus costs of installing headgates, etc.

†Downhill bank lining, only.

‡Diameter of tile.

Development of Best Management Practices for Salinity Control in Grand Valley

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ABSTRACT

Cost-effectiveness functions for various on-farm, conveyance, and desalting salinity control alternatives were developed for the Grand Valley of western Colorado. These functions were then optimized to determine the best management practices on a valley-wide scale. The results indicate the relative importance of lateral linings and on-farm improvements over either canal lining or desalting. Generalized curves are presented for application of this analysis to other similar areas where less information is available.

INTRODUCTION

The array of potential practices which can be applied in an irrigated region to improve the quality of irrigation return flows, or reduce the impact of these discharges on receiving waters, might include such structural changes as canal and lateral linings, drainage, and conversion to more site-suitable irrigation systems. In addition, improved irrigation practices could also produce benefits. For instance, aiding the irrigator with an irrigation scheduling service to maximize his water application efficiency would diminish the volume of irrigation return flows. Various other improvements in designs or practices might be noted, some of which would be more applicable than others to the multitude of conditions which exist in irrigated areas in the western United States.

The costs associated with water quality problems and the measures necessary for their resolution are generally high, particularly when the problem results from irrigated agriculture. It is therefore important to implement only the management alternatives which promise the most cost-effective treatment of the problem, subject of course, to environmental and political constraints. The ultimate use of research and demonstration data is in determining these best management practices to be implemented for the solution to the water quality problem.

The Grand Valley in western Colorado contributes substantially to the serious salinity problem in the Colorado River Basin, and has therefore, been given considerable attention not only to remedying its particular impact but also in testing methodologies for application to similar areas. A previous paper in this case study described the efforts made to quantify the components of the valley's complex hydro-salinity system and the demonstrations of alternative management practices. These results provided the data necessary to determine the optimal policies for implementing a salinity control program. The purpose of this paper is to summarize the procedure and illustrate the results for the Gand Valley case study.

GENERAL APPROACH

Optimizing the alternatives for managing salinity implies that the relationships between costs (or benefits) and salinity reductions are known. These cost-effectiveness functions are then fashioned into a format suitable for an optimizational analysis (minimization of costs or maximization of benefits, for example), and the optimal is computed. In mathematical terms:

$$Z = \min \sum_{i=1}^{n} f_i (X_i) \qquad (1)$$

in which,

Z = objective function; and

$f_i(X_i)$ = cost of implementing the ith alternative at a level X_i.

Equation 1 is of course restricted by a set of constraints such as:

$$\sum_{t=1}^{n} X_i \geq \overline{X}_i \qquad (2)$$

$$X_i \leq X_{Ti} \qquad (3)$$

where,

$\overline{X}_i$ = total expected level of control (expressed in metric tons); and

X_{Ti} = total control achievable through the ith alternative, in tons.

It should be noted that $f_i(X_i)$ is itself the product of an optimization analysis at what might be called a "lower level" of detail. For instance, if $f_i(X_i)$ represented the cost strategy for lining the conveyance channels, it could not be compared to a similar function for on-farm improvements unless both were minimum cost relationships. Thus, the cost-effectiveness function for the individual elements in the conveyance network must be evaluated in an optimization framework to determine $f_i(X_i)$.

As one readily observes, determining the best management practices on a basin-wide scale involves successive analyses at succeedingly smaller subdivisions of the problem structure. Analysis of individual feasibilities for conveyance, on-farm, and drainage improvements yield three functions which can be evaluated to give a single representation of the best valley-wide practices. Similar comparisons among the valley relationships yield strategies describing the optimal level of abatement in each individual irrigated area and a function describing the cost-effectiveness of agriculturally related salinity management. And finally, a comparison of cost for controlling salinity from agriculture with similar expressions for municipal, industrial, and natural sources determines the appropriate emphasis on agriculture as well as an estimate of the total costs for improving downstream water quality.

The flow of this discussion can be reversed to determine the intermediate details comprising a basin-wide salinity control strategy. For example, examination of the basin plan would delineate the level of investment in irrigated agriculture. The allocation of spending among irrigated areas would be derived from the policies regarding each irrigated area, etc. A diagrammatic view of this basic approach using levels to represent the valley-to-basin progression is presented in Figure 1.

The level of analysis for the Colorado River salinity problem is currently at the irrigated area level for only one major region (Grand Valley). At this time, implementation plans have already been developed for the valley without sufficient evaluation of respective feasibility. Consequently, the efforts in the immediate future may be extremely suboptimal as the results shown later in this paper will demonstrate. Unfortunately, these decisions were necessary before this analysis could be developed, but hopefully this analysis will alter present plans for implementation of a salinity control program in Grand Valley.

In the following sections, these concepts will be demonstrated for the Grand Valley case study. Four major management alternatives will be evaluated: (1) on-farm structural and operational improvements; (2) lateral lining by concrete or plastic pipe; (3) canal linings; and (4) desalting of collected return flows.

On-Farm Improvements

In the Grand Valley, approximately 27% of the flows diverted for irrigation are actually consumed through cropland evapotranspiration. This is only slightly more than the valley's total conveyance seepage and deep percolation losses (24%). From an efficiency stand point, the following definitions and values will give the reader a perspective of irrigation efficiency in this area:

1. Conveyance Efficiency $= \dfrac{\text{Diversions - Seepage}}{\text{Diversions}}$ $= 87\%$

2. Operational Efficiency $= \dfrac{\text{Diversions - Surface Wastes}}{\text{Diversions}}$ $= 46\%$

3. Farm Efficiency $= \dfrac{\text{Cropland Evapotranspiration}}{\text{Farm Deliveries + Precipitation}}$ $= 39\%$

4. Application Efficiency

$$= \frac{\text{Cropland Evapotranspiration}}{\text{Farm Deliveries-Tailwater} + \text{Precipitation}}$$

$$= 64\%$$

On-farm water management improvements may be divided into four general categories: (1) improved irrigation practices implemented through irrigation scheduling; (2) structural rehabilitation; (3) conversion to more effective irrigation methods; and (4) field drainage.

Irrigation Scheduling

Recent studies by the writers in Grand Valley have indicated that irrigation scheduling services, even when accompanied by flow measurement structures, generally do not improve farm and application efficiencies by more than 5-10% (Skogerboe, et al., 1974a). A westwide review of irrigation scheduling by Jensen (1975) indicated that a 10% improvement (from 40 to 50%) is realistically possible without system conversions or more energy intensive operations. In the Grand Valley, an irrigation scheduling service which included water measurement and farmer training would cost an estimated \$30/ha and would reduce return flow salinity by about 20,000 metric tons annually. Since it is not known how irrigation efficiencies may be distributed it is assumed that these figures may be linearly extrapolated yielding a cost-effectiveness function for irrigation scheduling of \$37.50/ton with a limit of 20,000 metric tons amenable to this approach.

The overall impact of irrigation scheduling being only 10% of the total estimated on-farm potential improvement is insignificant by itself when considering the sensitivity of these type of costing estimates. Consequently, irrigation scheduling is not considered a separate alternative salinity control measure, but rather taken to be an integral part of each of the remaining remedies. This assumption is particularly valid when viewing the costs of the other alternatives (irrigation scheduling's low cost would result in its inclusion in any implementation policy generated by an optimizational analysis).

Structural Rehabilitation

Irrigation efficiency can often be substantially improved by rebuilding and remodeling existing systems. The most commonly employed irrigation methods in the west are those generally classified as surface irrigation methods (furrow, border, or basin). Structural improvements in this system may include concrete lined head ditches and gated pipe to reduce seepage losses, land leveling for better water application uniformity, adjusting field lengths and water application rates to be more congruent with soil and cropping conditions, and automation to provide better water control. Flow measurement and scheduling services should accompany these types of improvements in order to maximize their effectiveness.

In the Grand Valley, head ditch requirements are generally less than the capacity of the smallest standard ditch available through local contractors (12-inch, 1:1 side slope, slip form concrete). Consequently, lining costs can be expected to be linearly distributed. In an earlier paper, an equation was presented to estimate concrete lining costs:

$$C_c = 40.1Q^{0.56} \tag{4}$$

where,

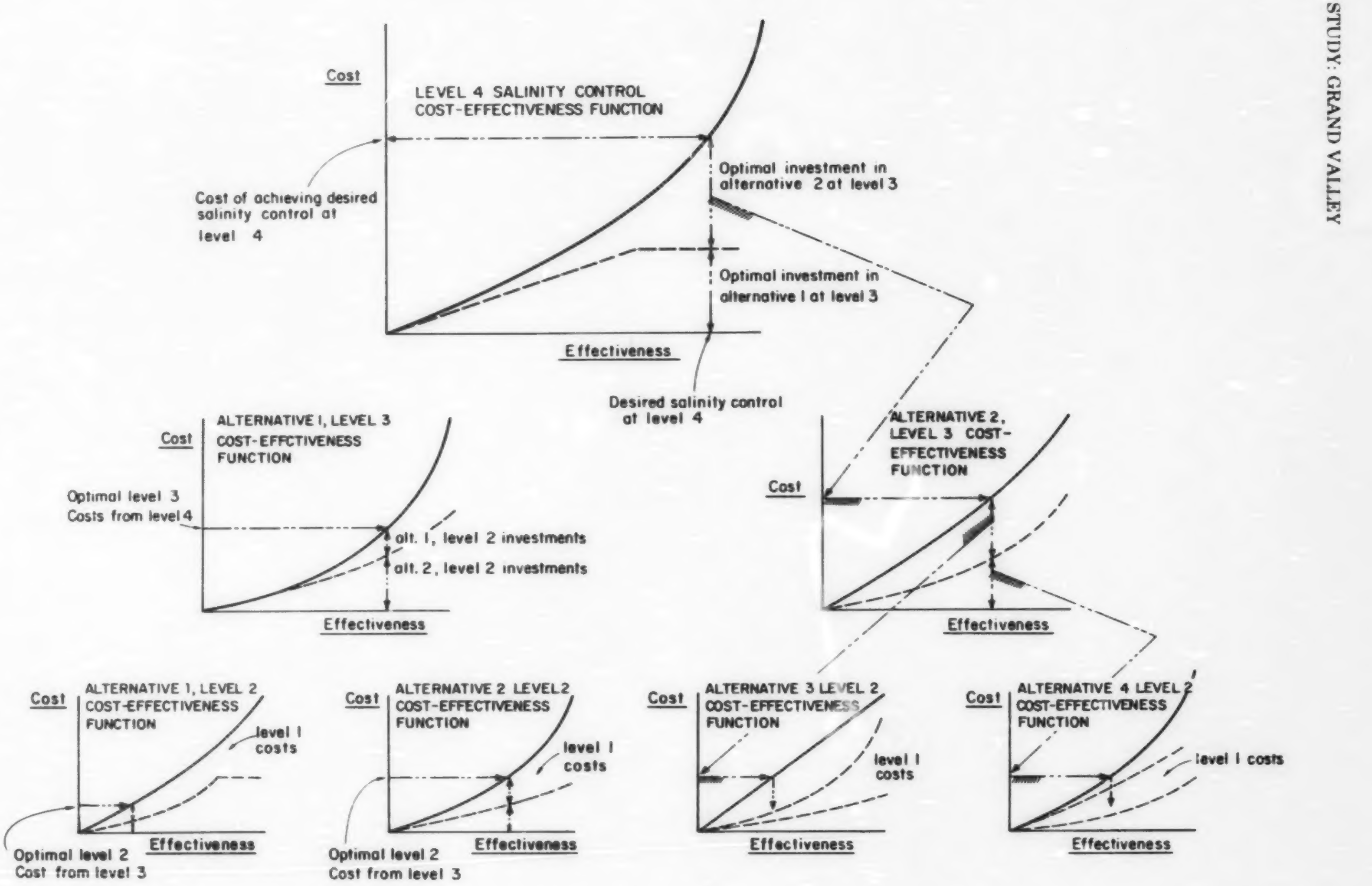
C_c = total lining cost, \$/m; and

Q = channel capacity, m^3/sec.

Assuming an average head ditch capacity of 0.05 m^3/sec, Equation 4 yields an estimated unit cost of \$7.50/m. This figure is well within the range encountered in the last two seasons in the valley. As an alternative to concrete linings, six-inch diameter aluminum pipe costs almost exactly the same. Thus, both improvements could be arbitrarily substituted with equal cost-effectiveness depending on farmer preference. There are approximately 1.3 million meters of head ditches in the Grand Valley contributing an estimated 30% of the total salt load from on-farm sources. As a result, the cost-effectiveness of head ditch improvements is \$113.50/ton. The limit of salt reductions through head ditch linings is about 86,000 tons annually.

Adjusting field lengths and land leveling probably has little or no salinity related benefits in the valley because infiltration rates are so low. In fact, advance rates are approximately 25% of the irrigation interval and uniformities are already high.

Automatic cutback furrow irrigation systems have demonstrated which when combined with irrigation scheduling, may improve irrigation efficiencies 15 to 20% (Evans, 1976)


Cost
LEVEL 4 SALINITY CONTROL
COST-EFFECTIVENESS FUNCTION
Cost of achieving desired salinity control at level 4
Optimal investment in alternative 2 at level 3
Optimal investment in alternative I at level 3
Effectiveness
Desired salinity control at level 4
Cost
ALTERNATIVE I, LEVEL 3
COST-EFFCTIVENESS FUNCTION
Optimal level 3 Costs from level 4
alt. I, level 2 investments
alt. 2, level 2 investments
Effectiveness
ALTERNATIVE 2, LEVEL 3 COST-EFFECTIVENESS FUNCTION
Cost
Effectiveness
Cost
ALTERNATIVE 1, LEVEL 2
COST-EFFECTIVENESS FUNCTION
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Optimal level 2 Cost from level 3
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COST-EFFECTIVENESS FUNCTION
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Optimal level 2 Cost from level 3
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ALTERNATIVE 3 LEVEL 2
COST-EFFECTIVENESS FUNCTION
level I costs
Effectiveness
Cost
ALTERNATIVE 4 LEVEL 2
COST-EFFECTIVENESS FUNCTION
level I costs
Effectiveness

Figure 1. Illustration of the multi-level, multi- divisional nature of optimal management policies for regional salinity control.

In 1975, the installed cost of the cutback systems was \$11.50/m. Thus, in addition to the salt load reductions by lining the head ditch (86,000 tons), an additional 60,000 m ton reduction could be expected due to increased irrigation efficiency. The resulting cost effectiveness is then computed as \$102.50/ton, again assuming a linear distribution. In the case of the Grand Valley, it appears more cost-effective to implement a more costly but efficient improvement for the additional efficiency related salinity reductions which are possible.

For other areas, where head ditch capacities are large, concrete lining would generally be more cost-effective than piped systems. Whether or not automated cutback would enjoy the advantage over regular linings would require evaluation under those specific conditions.

System Conversion

In order to completely control the quality and quantity of irrigation return flows in an area like Grand Valley, irrigators would need to convert their irrigation to either sprinkler or trickle irrigation systems. Then with proper management, irrigation efficiencies could be improved to 75-85% with sprinklers and 90-95% with trickle systems. Portable or mobile sprinkler systems (not including center-pivot types) for the Grand Valley condition are costing approximately \$1250/ha with solid set sprinklers and automated trickle systems approximately double this figure. At the time of this writing, we have not evaluated these two irrigation methods in sufficient detail to confirm their respective feasibilities. However, it appears the added efficiency of trickle systems is about equally offset by the higher costs. Consequently, within the sensitivity of the estimates, sprinkler and trickle systems enjoy about the same advantage and could be applied where individual circumstances dictate. The Grand Valley cost-effectiveness for pressurized irrigation systems is computed to be approximately \$145/ton and could be expected to essentially eliminate excessive deep percolation (beyond leaching requirement) and field tailwater. However, these systems are much more energy intensive which was not given major attention in this paper.

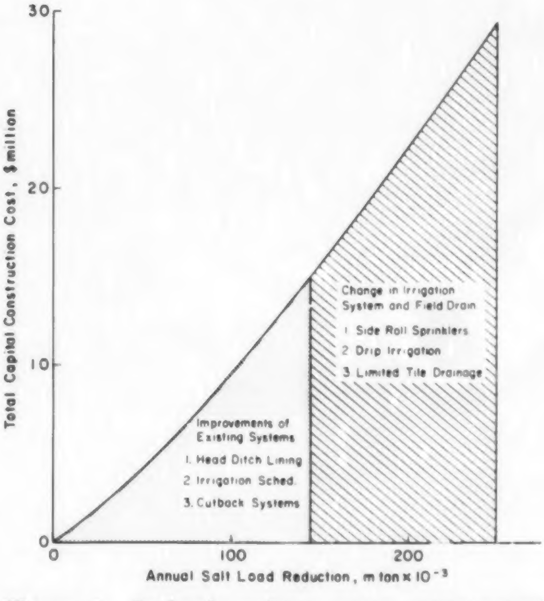

Figure 2. Optimal on-farm water management strategies in the Grand Valley.

Field Drainage

The low permeability of Grand Valley soils dictate relatively close drain spacings (12-24 meters). Although field drainage has been proven partially effective in reducing salt pickup (Skogerboe, et al., 1974b), the costs are so high that drainage would not be competitive with other salinity control measures. Therefore, we will not offer further consideration to drainage in this paper.

Optimal On-Farm Improvement Strategies

The cost-effectiveness relationships for the previously described on-farm improvement possibilities were examined in an optimization context. The results shown in Figure 2 are interesting. Total capital costs in millions of dollars were plotted against the expected reduction in annual salt load from the valley for the minimum cost array of practices. The curve agreed with data reported recently by the Soil Conservation Service in a public information brochure.

Two major strategies evolved in the analysis of on-farm improvements: (1) improvements to the existing system creating salinity reductions up to about 150,000 tons; and (2) system conversions to provide controls up to approximately 250,000 tons. Of particular interest here, is the fact that both alternatives are mutually exclusive. In other words, in implementing an on-farm salinity management plan, either one or the other is optimally chosen. For instance, if planners selected on-farm improvements to reduce salinity by more than 150,000 tons, the alternatives would be limited to changing to sprinkler and drip irrigation methods. Below the 150,000 ton figure, improvements to the existing systems would be optimal. This structure of the cost-effectiveness functions is unique among the alternatives as the reader will note in succeeding sections. This uniqueness is based on the fact that on-farm improvements themselves are mutually exclusive and limited in their expected effectiveness. For example, head ditch linings would not be considered in the conversion to a sprinkler system.

Lateral Lining and Piping

We have defined laterals as the small capacity conveyance channels transmitting irrigation water from the supply canals and ditches to the individual fields. Most of these laterals operate in a north-south direction and can carry the flows in relatively small cross-sections. Although the capacities of the laterals may vary between 0.06 and 1.4 m^3/sec, most capacities would be within the range of 0.06 to 0.20 m^3/sec. Utilizing a median value of 0.20 m^3/sec yields a concrete lining cost of approximately $16/m. Alternative use of PVC pipe approximates concrete lining costs for this capacity and a further distinction will not be made. However by this assumption we are neglecting the small seepage losses which would still occur from concrete lined channels.

An earlier paper noted that Grand Valley laterals extend approximately 600,000 meters, less than one half the length of field head ditches. Seepage under existing conditions contributes about 202,000 metric tons, or slightly less than the on-farm contribution. Although no attempt was made to distribute the lateral lining costs to account for variable capacity (at least for the purposes of this paper), the cost-effectiveness function for Grand Valley lateral lining is about $49.50 per metric ton. Thus, the estimated costs of lining the total lateral system in the valley is about $10 million.

Canal Lining

The analysis of canal and ditch linings for the Grand Valley was presented in an earlier paper of this conference by the senior author entitled, "Combining Agricultural Improvements and Desalination of Return Flows to Optimize Local Salinity Control Policies." The results are repeated in Figure 3, in which the upper curve represents the minimal cost curve. At any point along this curve, a vertical cost distribution among the alternative canals indicates the optimal investment in each system.

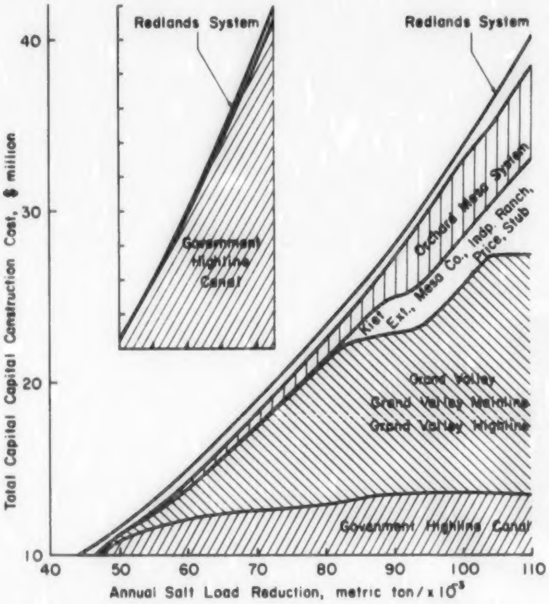

Figure 3. Minimum cost canal and ditch lining strategy for the Grand Valley.

Desalination

Application of desalting technology was also discussed in the earlier paper mentioned above. These results will not be reiterated here other than to say a desalting cost-effectiveness function for the Grand Valley assuming pump drainage, reverse osmosis, and deep well injection of brines would be approximately linear at $310 per metric ton of salt removed.

Determining Best Management Practices

The individual cost-effectiveness functions for each previously discussed alternative can be integrated to determine what might be called an optimal overall policy for the Grand Valley. To present this on a somewhat general basis, the distribution of the cost effectiveness functions has been computed and presented in Figure 4. Lateral linings and desalting are represented as linear distributions

$$\overline{Y} = \overline{X} \tag{5}$$

in which

$\overline{Y}$ = fraction of the total costs; and

$\overline{X}$ = fraction of the total potential salinity reduction associated with the linings.

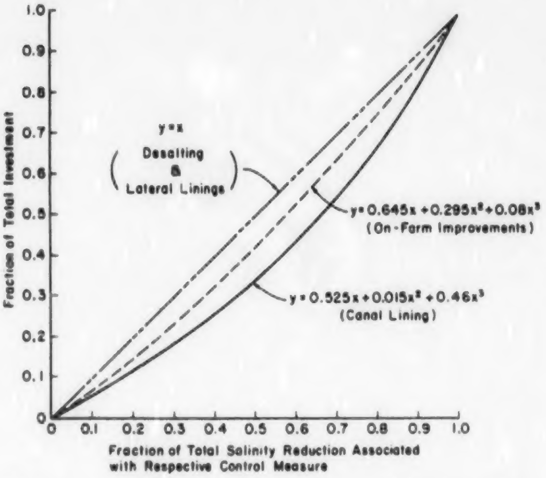

Figure 4. Distribution of cost-effectiveness functions for the primary salinity control alternatives in the Grand Valley.

Equation 5 assumes that the total costs achieve the potential salinity reduction attributable to that specific measure, with the potential being the measure of maximum effectiveness. For on-farm improvements and canal linings, respectively

$$\overline{Y} = 0.645\overline{X} + 0.295\overline{X}^2 + 0.08\overline{X}^3 \tag{6}$$

$$\overline{Y} = 0.525\overline{X} + 0.015\overline{X}^2 + 0.46\overline{X}^3 \tag{7}$$

The appropriate limits can be substituted into Equations 5-7 to yield the problem's objective functions. For desalting, the liner structure provides that:

$$Y_d = 310\, X_d \tag{8}$$

where,

Y_d = capital cost of removing X_d metric tons from the irrigation return flow system.

similarly for lateral linings:

$$Y_l = 49.50\, X_l \tag{9}$$

For the on-farm improvements:

$$Y_f = 29.7 \times 10^6 \left[0.645\left(\frac{X_f}{2.5 \times 10^5}\right) + 0.295\left(\frac{X_f}{2.5 \times 10^5}\right)^2 + 0.08\left(\frac{X_f}{2.5 \times 10^5}\right)^3\right] \tag{10}$$

and canal linings:

$$Y_c = 40.\text{x}10^6 \left[0.525\left(\frac{X_c}{1.1\text{x}10^5}\right) + 0.015\left(\frac{X_c}{1.1 \times 10^5}\right)^2 + 0.46\left(\frac{X_c}{1.1 \times 10^5}\right)^3\right] \tag{11}$$

where the 1.1x10^5 factor in Equation 11 is the salt reduction possible from canal ditch linings as reported in an earlier paper. The objective function is therefore:

$$Z = \min\left[Y_d(X_d) + Y_l(X_l) + Y_f(X_f) + Y_c(X_c)\right] \tag{12}$$

in which the individual costs are represented as functions of the expected salt reduction. Equation 12 must be constrainted to account for the maximum potential of each approach. Thus,

$$X_l \leq 202{,}000 \text{ tons} \tag{13}$$

$$S_f \leq 250{,}000 \text{ tons} \tag{14}$$

$$X_c \leq 110{,}000 \text{ tons} \tag{15}$$

and,

$$X_d + X_l + X_f + X_c = X_T \tag{16}$$

where,

X_T = the total combined effectiveness to be achieved, tons.

The result of this analysis for a wide range of X_T's is shown in Figure 5.

DISCUSSION

In representing what we have chosen to call the best management practices for the Grand Valley, Figure 5 deserves several explanatory notes. First, it must be realized that the four major implementation alternatives (lateral lining, on-farm improvements, canal linings, and desalting) only represent what might be denoted as "structural measures." Consequently, non-structural alternatives such as land retirement, influent and effluent standards, taxation, and miscellaneous enforcement options are not included. The structural improvements would, however, consider irrigation education (irrigation scheduling and extension) type activities.

The second point which should be examined is the value of this sort of analysis. In Grand

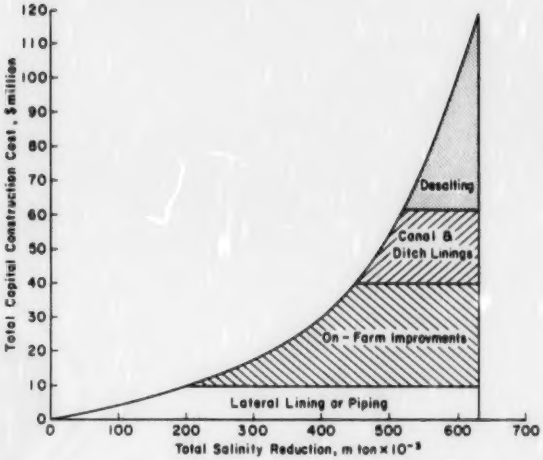

Figure 5. Minimum cost salinity control strategy for the Grand Valley.

Valley, existing plans call for the lining of canals, ditches, and laterals in combination with some on-farm improvements. Desalting is probably not being considered. Canal linings would cost approximately 40 million dollars (in 1976 costs) and reduce salinity 110,000 tons. Lateral lining is estimated to cost about $30 million by the Bureau of Reclamation, but should be possible for at least one-third this figure (10 million dollars) and would reduce salinity by about 202,000 tons annually. Under their most intensive plan, the Soil Conservation Service estimates that $23 million could be spent for on-farm improvements to produce a 209,000 ton improvement. (Our figures indicate that $23 million would impact on-farm salt sources by 205,000 tons annually.) Therefore, 73 million dollars would be invested in improving irrigation return flow quality by an equivalent 517,000 tons ($141.20 per ton). Examination of Figure 5 indicated that a salt load reduction of 517,000 tons could be achieved at a cost of only $57 million by using less canal lining and increasing on-farm improvements. This is a savings of more than 25% or 16 million dollars.

A third point of interest is "How much salinity control is feasible, given current estimates of downstream detrements?" Walker (1975) reviewed much of the literature descriptive of the California, Arizona, and Republic of Mexico damages. At that time, Valantine (1974) had proposed damages of $175,000 per mg/l of increase at Hoover Dam ($146 per ton in Grand Valley assuming 8% interest). Other estimates in terms of equivalent damages attributable to Grand Valley range upward. A representative figure is $190/ton as proposed by the Bureau of Reclamation (Leathers and Young, 1976). If the minimum cost curve in Figure 5 is differentiated to approximate marginal costs and be congruent with these damage figures, the $146 per ton damage estimate of Valantine (1974) falls at a 400,000 ton reduction, while the $190 per ton occurs at 450,000 tons. Thus, not considering secondary benefits in the Grand Valley, or obviously all the consequences in the lower basin, the level of investment in the Grand Valley should not exceed $30-40 million. Otherwise, the costs are apparently not justified by the damages and another salt contributor should be evaluated for possible control. Our conclusion is, therefore, considering the preliminary stage of analysis encompassed by this paper, the best management practices for the Grand Valley should be limited to on-farm improvements and lateral linings. If downstream damage can be shown to be higher, then limited canal lining should proceed. Furthermore, irrigation improvements should consist of conversion to other methods rather than treatments of the existing system. This conclusion could of course be amended if local farmers would adapt the measures necessary to achieve 85-90% surface irrigation efficiencies (which would imply mandatory compliance with irrigation scheduling criteria and comprehensive automation).

And a final point to be made herein concerns the sensitivity of these results to the assumptions in the analysis. Our estimates would need to be approximately 100% wrong to affect the respective feasibility of lateral linings versus on-farm improvements, and roughly the same between the remaining alternatives. Such magnitudes of error are improbable given the years of experience and the level of research effort applied to the Grand Valley by the authors and many other federal and state agencies.

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Implementation

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The EPA General Permit Program

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ABSTRACT

The Environmental Protection Agency (EPA) has developed a General Permit Program under the National Pollutant Discharge Elimation System (NPDES) which applies to both separate storm sewers and agricultural point sources (irrigation return flow conveyances). The proposed rules for this general permit program were printed in the Federal Register, Vol. 42, No. 24, February 4, 1977. This paper provides a guide as to how the General Permit Program is intended to function.

Purpose for the General Permit Program

The regulations are being developed to comply with the court order following the case of *NRDC v. Train*, better known as the Flannery decision. That decision required EPA to develop and administer a permit program for all point sources in the feedlot, separate storm sewer, agriculture and silviculture categories. The conventional NPDES permit program was applied to feedlots and silvicultural point sources, but this general permit program will be applied to separate storm sewers and agricultural point sources (irrigation return flow conveyances). The discharge sources affected by this general permit program are defined for separate storm sewers at page 11303, and for agricultural point sources at page 28493, both in volume 41 of the *Federal Register*.

Goals

This general permit program is being proposed to meet the following goals:

A. To enable the permit-issuing agency to issue an authorization to discharge to a number of people with one simplified administrative procedure. This will allow the agency to focus its attention on the most severe pollution problems.

B. To enable the permit-issuing agency to coordinate better with forthcoming 208 and other local plans. Because universally applicable techniques for controlling and abating pollution from separate storm sewers and agricultural point sources are currently unavailable, locally-oriented areawide plans will better determine what pollution reduction practices are required.

C. To progress towards a comprehensive, well-managed and effective program for improving water quality. Much needs to be done to gather information; develop pollution control practices and technology; and enhance cooperation among affected persons and groups,and involved local, State and Federal agencies. General permits will help define the problem, establish priorities and direct resources toward these ends.

D. To provide flexibility of approach. The problems faced by owners and operators of separate storm sewers and agricultural point sources vary considerably throughout the country. This proposed program provides a number of options for dealing with different problems and thus allows for maximum flexibility within the requirements of the court order.

Outline of the Program

If these regulations are finalized in the same form as they are proposed, the following outline shows the steps the Federal government will take to administer the program.

Step 1: The Regional Administrator will draw a map of the area in which a general permit will be issued. This area is called a general permit program area (GPPA) and could cover separate storm sewers or agricultural point sources, or both.

Step 2: The Regional Administrator will publish a notice in local papers and post a notice in public places in the

GPPA saying that he is proposing to issue a general permit affecting all owners and operators of separate storm sewers and/or agricultural point sources in that area. The notice will also indicate what kinds of conditions the affected owners and operators may be subject to under the proposed general permit.

Step 3: The Regional Administrator will also send copies of the proposed general permit to the District Engineer of the Corps of Engineers, the U.S. and State agencies for agriculture and commerce, the appropriate 208 planning agencies and the State water pollution control agency in the State where the discharge will occur. These agencies and organizations may then comment on the general permit as proposed.

Step 4: After the notice is published and posted, affected owners and operators have at least 45 days to comment on the proposed general permit. If any person wants more information or would like to request a public hearing on the proposed general permit, those opportunities will be available.

Step 5: If several persons request a public hearing, the Regional Administrator may hold a hearing to gather information concerning the proposed general permit and to hear the opinions of the persons present. In holding a public hearing the Regional Administrator will make sure that all those persons who would be interested in it will be notified of the time, date and place, and other pertinent information.

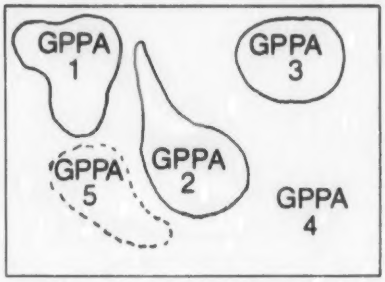
Step 6: After a public hearing, the Regional Administrator will consider all the comments received on the proposed general permit and make final determinations on whether to issue the general permit as proposed or to modify it in some way. If the proposed general permit remains intact, it will probably become effective in a month. If the general permit is substantially modified from when it was first proposed, the Regional Administrator will publish and post the changes as he did the original notice.

Step 7: After the conditions of the general permit have been finally determined, the permit will be published in the *Federal Register* and in other appropriate places in the area of the GPPA. Any person wanting an individual copy of the permit may request one from the Regional Administrator. Once the general permit becomes effective, all affected owners and operators must comply with the permit's terms and conditions.

Step 8: Should any affected persons disagree with the terms and conditions of the general permit, that person may request an evidentiary hearing (also known as an adjudicatory hearing) within 10 days after the general permit is published in the *Federal Register*. Any request for an evidentiary hearing will be handled like those requests under the conventional NPDES program.

It should also be noted that not every owner or operator of any agricultural point source or separate storm sewer may agree with the general permit approach. Indeed, some such owners or operators already *have* conventional individual NPDES permits, and would prefer to remain subject to those permits rather than to be subject to a new general permit. Thus, it is EPA's intent to allow those owners or operators to keep their individual permits as they so desire. In fact, even owners or operators of agricultural point sources or separate storm sewers who do not currently hold NPDES permits have the option to apply for individual permits rather than be subject to the general permit. Procedures for obtaining such an individual NPDES permit are set forth in the proposed regulations.

A Graphic Example of the General Permit Program



The NPDES permit program is administered by EPA in State A. The Regional Administrator has designated four (4) GPPAs in State A as follows:

GPPA 1: This area, defined by the boundaries of a major river basin, is primarily agricultural and is populated by hundreds of owners and operators of agricultural point sources (irrigation return flow ditches). There is no substantial water quality problem in this area, but the potential for water quality problems is recognized. However, this GPPA is not yet identified as a high priority area for water quality improvement. Because of the recognized potential for water quality problems, however, the general permit for this GPPA requires owners and operators of agricultural point sources to submit reports of any sampling they do. The general permit does not require sampling at this time, but the term of the permit is only 3 years so that the need for sampling may be reassessed in the near future. The general permit for this GPPA would resemble the sample general permit included as Part VI of this guide.

GPPA 2: This area, defined by the boundaries of a large Bureau of Reclamation project, is primarily agricultural and is populated by hundreds of owners or operators of agricultural point sources (irrigation return flow ditches). Unlike GPPA 1, this area has long been recognized as plagued with water quality problems, particularly siltation. For many years the conservation districts have worked with the farmers in the area to reduce erosion and thereby decrease economic losses and improve water quality. When the 208 agency identified this area as having significant water quality control problems, it began to coordinate its water pollution control activities with ongoing programs, and together with local agricultural colleges and organizations devised a 20-year plan for implementing proven techniques to reduce siltation. The first 5 years included plans to educate farmers to the program, to train them in the techniques to be implemented, to work with cost-sharing programs for aid, to introduce appropriate legislative changes, and to begin action in increasing the width of grass filter strips and planting appropriate protective vegetation. The local and State governments of this area will devise and enforce ordinances and regulations which will ensure the implementation of this plan. If regulatory programs are not implemented satisfactorily then the general permit may be strengthened with more substantial requirements.

GPPA 3: This area, defined by city limits, is primarily urban and contains several publically- and privately-owned separate storm sewers. There is a recognized water quality problem, but techniques to solve the problem have not been fully developed, primarily because there is a lack of information about the pollution and where it comes from. No 208 plan requirements have been set forth as yet. However, because of the need for information, the general permit requires each owner or operator to register with the permit-issuing agency, reporting information on the number and location of outfalls of their separate storm sewer systems. Monitoring and reporting may be general permit requirements at a later date.

GPPA 4: This area is both urban and rural and encompasses all that area of the State not specifically identified as GPPAs 1, 2 and 3. No serious water quality problems are currently recognized by the 208 agency, and thus it has been determined that no exceptional requirements need be imposed through the general permit. Thus, the permit simply authorizes all owners and operators of separate storm sewers and agricultural point sources to discharge from those sources, subject only to the standard language of the general permit. If water quality problems are recognized at a later date, regulatory measures to control these problems must be devised. If these regulatory measures prove ineffectual, then the general permit may be revoked as to a portion of the area (GPPA 5), and a new general permit, containing more specific and stringent requirements, may be imposed.

The variations in the form and requirements of any general permit are dependent on several factors:

1) The severity of the water quality problem.
   - Does it affect health?
   - Does it affect drinking water sources?
   - Does it affect recreation facilities or aesthetics?
2) The context in which the water quality problem occurs.
   - What will be the economic impact on the area if the problem is corrected?
   - What will be the economic impact on the area if the problem remains unsolved?
   - What are the political ramifications of solving the problem?
3) The interest of the persons affected by the water quality problem.
   - Are farmers interested in solving the problem?
   - Are cities interested in solving the problem?
   - What is the reaction of the community?
   - What is the role of EPA in solving the problem?
   - What is the role of the State and local governments in solving the problem?
   - Is an environmental group particularly interested in the problem?
4) The timetable in which other developments occur.
   - When does the 208 agency complete its plans?
   - When do other plans and developments impacting separate storm sewers and agricultural point sources contemplate implementation?
   - When are research, development and demonstration projects complete and ready for functioning?
   - When are effluent guidelines promulgated or appropriate technology identified?

Ten Most Asked Questions

1) What will a general permit look like?

A general permit could take many forms depending for the most part on the variations listed above. An example of a possible general permit for southwest Iowa is set forth later in this guide as a sample for an area where it is assumed there is no current or potential water quality problem. As you can see, it applies to all owners and operators of separate storm sewers and agricultural point source in an area of 8 counties. It contains some standard prohibitions and other language relating to the legal responsibilities of the owners and operators. It contains very few mandatory provisions requiring action on the part of most owners and operators. For those owners and operators who do sample their discharge, reporting of that sampling is required.

2) Who is the permittee?

Under this general permit program there are few named permittees. In some areas, it may be feasible and desirable to name the permittees (city sewer districts, for example). However, in most cases the permittees will be referred to as the owners and operators of separate storm sewers and agricultural point sources. Owners and operators are those persons who own, operate or use the conveyances of separate storm sewers and agricultural point sources.

3) What about water quality standards?

EPA recognizes that State water quality standards will not be met overnight with the implementation of the general permit program. Meeting water quality standards is a long term project that will require the cooperation of many individuals, groups, organizations and government agencies. In close coordination, the affected persons should be able to work within the existing framework of 208 planning agencies, conservation district education and support, and other currently available and diverse mechanisms for improving water quality. Improved water quality is one goal of the general permit program, but it can only be met after increased efforts to coordinate this program with existing, ongoing programs that have the same outcome.

4) How does 208 planning fit into this general permit program?

Although it is still somewhat speculative exactly how the general permit program will coordinate with 208 plans, the theory is this: Plans developed under section 208 of the Federal Water Pollution Control Act are to identify areas with water quality problems and methods of solving such problems, including management practices and maintenance techniques and most importantly, regulatory measures to implement these practices and techniques. If these regulatory measures are insufficient, or unsuccessful, then an existing general permit could be modified, or individual permits might be issued in lieu of a general permit. Either a modified general permit or individual permits could then incorporate the practices and techniques identified in the 208 plan. For example, suppose a 208 agency identified the lower basin of a river as an area with water quality problems. In conjunction with the affected farmers of the area, the 208 agency arranges a water distribution and application agreement which will help abate the problem. Most of the farmers agree with the arrangement but some are hesitant about losing their water rights. Because 208 agencies are to develop institutional and legal mechanisms for bringing about the desired goals, legislation could be proposed to preserve all water rights so long as water is used in accordance with the agreement.

This is a very simplistic example, but it illustrates the flexibility of 208 plan as a management tool. It also illustrates the importance of the role of concerned citizens in the development of 208 plans.

5) Will farmers have to change the methods of their operations?

This will depend on the conditions of the general permit. EPA anticipates that the vast majority of farmers affected by the general permit program will not have to change the methods of their operations, particularly not in the near future. Changes may be necessary where water quality problems are identified. However, farmers should begin now to adopt management practices to protect water quality. Involvement in and cooperation with 208 planning agencies can not be overemphasized as a functio of concerned citizens and organizations. It is through such involvement and cooperation that the most effective, well-managed and best-accepted plans will evolve.

6) Is the general permit program legal?

Yes. Not only does the Federal Water Pollution Control Act not specifically exclude the possibility of general permits, Judge Flannery, as the interpreter of the Act in the NRDC case, specifically encouraged EPA to develop a flexibile administrative approach to dealing with separate storm sewers and agricultural point sources.

7) What will happen over the next two years in this area?

There are two anticipated developments.

A. This regulation will be promulgated in final form, the designation of GPPAs will take place, and general permits will begin to be issued.

B. Since all 208 plans are required to be submitted by November 1978, water quality control problems should be clearly identified and implementation of the plans should begin.

There is an additional *possible* development:

Better information and data could be developed which might make effluent guidelines feasible for agricultural point sources or separate storm sewers, if not uniformly, at least in portions of the Nation. This could pave the way for use of the conventional NPDES permits issued to individual owners and operators.

8) What do I have to do if I own a separate storm sewer or an agricultural point source?

Watch for notices in your area, most probably in the Fall of 1977, that you are in a GPPA for which a general permit is proposed to be issued. Take an active interest in its issuance. Attend the public hearing if one is held. Before next Fall find out about the 208 agency in your area — what it is doing about water quality problems you perceive in your area, what its plans are, how it will affect you, and how you can get involved.

9) What should I do if I'm affected by a water quality problem that I want to help abate?

Contact your State water pollution control agency and other local agencies that may not be aware of the problem, but that do have the authority to aid in its resolution. Conservation districts, land grant colleges, farmers' organizations, environmental action groups and other concerned persons are often invaluable sources of information and ideas. Again, the 208 and other planning agencies should be utilized as tools for solving such problems. Working together with these government and private organizations will help provide the appropriate mechanisms for cooperative effort to progress toward meeting water quality goals.

10) What should I do if I don't like this whole program?

Let your opinion be known Comment on the proposed regulations. Vocalize your doubts at the forums provided as part of the public information and public participation aspects of this regulatory process. As you know, EPA originally did not require permits for either separate storm sewers or agricultural point sources. However, as a result of a 1975 judicial interpretation of the law, EPA is now required to develop a permit program applicable to these point sources. Given this requirement EPA would appreciate any ideas for alternatives to this program. We value your input.

Sample Permit

Permit No. IA-GP00001

AUTHORIZATION TO DISCHARGE UNDER THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM

In compliance with the provisions of the Federal Water Pollution Control Act, as amended, (33 U.S.C. 1251 et seq; the "Act"),

All owners and operators of separate storm sewers as defined in 40 CFR 125.52 (a) (1) and all owners and operators of agricultural point sources as defined in 40 CFR 125.53 (a) (1)

are authorized to discharge from such separate storm sewers and agricultural point sources located in the following counties:

Pottawattamie
Cass
Mills
Montgomery
Adams
Fremont
Page
Taylor

Such discharges are authorized into the following rivers:

Missouri
W. Nishnabotna
E. Nishnabotna
Nishnabotna
Boyer
W. Nodaway
Middle Nodaway
E. Nodaway
Platte
and their tributaries,

in accordance with all conditions set forth herein.

This permit shall become effective on March 15, 1978.

This permit and the authorization to discharge shall expire at midnight, March 15, 1981.

Signed this ____ day of ________.

A. MANAGEMENT REQUIREMENTS

1. *Facilities Operation*

The permittee shall at all times maintain in good working order and operate as efficiently as possible any treatment or control facilities or systems installed or used by the permittee to achieve compliance with the terms and conditions of this permit.

2. *Adverse Impact*

The permittee shall take all reasonable steps to minimize any adverse impact to navigable waters resulting from noncompliance with any conditions specified in this permit.

3. *Bypassing*

Any diversion from or bypass of facilities necessary to maintain compliance with the terms and conditions of this permit is prohibited, except (i) where unavoidable to prevent loss of life or severe property damage, or (ii) where excessive storm drainage or runoff would damage any facilities necessary for compliance with this permit.

4. *Removed Substances*

Solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters shall be disposed of in a manner such as to prevent any pollutant from such materials from entering navigable waters.

B. LEGAL RESPONSIBILITIES

1. *Violations of Permit*

All discharges authorized herein shall be consistent with the terms and conditions of this permit. Any discharge from any separate storm sewer or agricultural point source inconsistent with the terms and conditions of this permit shall constitute a violation of the permit.

2. *Right of Entry*

The permittee shall allow the head of the State water pollution control agency, the Regional Administrator, and/or their authorized representatives, upon the presentation of credentials:

a. To enter upon the permittee's premises where an effluent source may be located or in which any records are required to be kept under the terms and conditions of this permit; and

b. At reasonable times to have access to and copy any records required to be kept under the terms and conditions of this permit; to inspect any monitoring equipment or monitoring method required in this permit; and to sample any discharge.

3. *Availability of Reports*

Except for data determined to be confidential under section 308 of the Act, all reports prepared in accordance with the terms of this permit shall be available for public inspection at the offices of the State water pollution control agency and the Regional Administrator. As required by the Act, effluent data shall not be considered confidential. Knowingly making any false statement on any such report may result in the imposition of criminal penalties as provided for in section 309 of the Act.

4. *Civil and Criminal Liability*

Except as provided in permit conditions on "Bypassing" (A.3.), nothing in this permit shall be construed to relieve the permittee from civil or criminal penalties for noncompliance.

5. *Oil and Hazardous Substance Liability*

Nothing in this permit shall be construed to preclude the institution of any legal action or relieve the permittee from any responsibilities, liabilities, or penalties to which the permittee is or may be subject under section 311 of the Act.

6. *State Laws*

Nothing in this permit shall be construed to preclude the institution of any legal action or relieve the permittee from any responsibilities, liabilities, or penalties established pursuant to any applicable State law or regulation under authority preserved by section 510 of the Act.

7. *Property Rights*

The issuance of this permit does not convey any property rights in either real or personal property, or any exclusive privileges, nor does it authorize any injury to private property or any invasion of personal rights, nor any infringement of Federal, State or local laws or regulations.

8. *Severability*

The provisions of this permit are severable, and if any provision of this permit, or the application of any provision of this permit to any circumstance, is held invalid, the application of such provision to other circumstances, and the remainder of this permit, shall not be affected thereby.

C. PERMIT MODIFICATION

After notice and opportunity for a hearing, this permit may be modified, suspended, or revoked in whole or in part during its term for cause including, but not limited to, the following:

a. Violation by any owner or operator subject to this permit with any terms or conditions of the permit;

b. A finding that circumstances have changed with respect to:

  (i) The availability of demonstrated technology or practices for the control or abatement of pollutants from separate storm sewers or agricultural point sources;

  (ii) The availability of effluent guidelines for separate storm sewers or agricultural point sources;

  (iii) The availability or implementation of an approved 208 plan; or

  (iv) The amounts, rates or concentracentrations of pollutants discharged from point sources covered by the general permit;

c. An act of God, flood, drought, materials shortage, or other event over which the owners or operators subject to the general permit have no control;

d. Issuance of individual NPDES permits for all point sources in a GPPA.

D. PERMIT REQUIREMENTS

1. *Monitoring and Reporting*

The results of any monitoring done by any owner or operator of a separate storm sewer or agricultural point source subject to this permit shall be recorded by such owner or operator. Any such reports shall be summarized biannually and submitted to the Regional Administrator and the State at the following addresses:

Water Division
Environmental Protection Agency,
Region VII
1735 Baltimore Avenue
Kansas City, Missouri 64108

Iowa Department of Environmental
Quality
Lucas State Office Building
Des Moines, Iowa 50319

Such summary shall include:

a. The name and address of the person submitting the data;
b. The places and dates of monitoring,
c. The dates of analysis;
d. The persons who performed the analysis;
e. The analytical techniques used; and
f. The results of the analysis.

2. *Effluent Limitations*

No owner or operator of a separate storm sewer or agricultural point source subject to this permit shall discharge into navigable waters.

1. Any radiological, chemical, or biological warfare agent;
2. Any high-level radioactive waste;
3. Any pollutant in violation of State certification;
4. Any pollutant in violation of limitations or prohibitions established under section 307(a) of the Act; or
5. Any pollutant in violation of specific requirements authorized under sections 208 and 209 of the Act.

Interface of Water Quantity and Quality Laws in the West

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ABSTRACT

Water pollution from irrigated agriculture in the West has received major attention during the past five years, primarily as a result of federal and state endeavors to identify irrigation return flow quality problems and to develop a viable control strategy. The national goal of "cleaner water" emerged as a result of the deterioration of water quality by degraded discharges from various sources.

The key to irrigated agricultural return flow quality control is proper utilization and management of the resource itself, and an accepted tool in our society is the law. By legal classification, it is divided into laws for quantity control and laws for quality control. The laws on water quality control are recent, relatively uniform between states and with little exception, constrain improvement of return flows from irrigated agriculture. Unfortunately, in most others, they cannot really be said to facilitate this consequence either. The laws pertaining to water resources quantity control and management are complex, voluminous, inconsistent and lack uniformity among the seventeen states of the West.

Directly affecting the management of water in the West is the water right designed to provide the water user with the same constitutional guarantees extended to real property. The resulting effect upon agricultural users is that certain rigidities in the exercise and protection of the right inhibit adaptation of more efficient practices. Furthermore, the water right holder is primarily concerned with his immediate geographic area, and not with the effects from exercising his right upon downstream users who may be in another state and themselves subject to different rules and regulations.

It can only be anticipated that in the near future greater uniformity in the water laws among the states and in water use efficiency criteria will occur. The recognition of the interdependence of water quantity allocation and water quality control for agricultural use is imperative. In spite of several federal efforts to introduce regulations to control this pollution discharge, strong resistance and little success summarizes the status. The state agencies, particularly the water quality agencies, are very much concerned with the implementability of any program to control irrigation return flow quality. Unless the nature of the problem is incorporated into the law and its administration, water users cannot be expected to act in a manner different from historical patterns.

WATER QUANTITY LAWS IN THE WEST

A System of Water Law

Water law in the United States is a "federal" system with a delineation of jurisdiction over water at the national and state government levels. Federal government water law is uniform and nation-wide with regional flexibility in the implementing agency regulations. But, each of the fifty states adopted quantity control surface and ground water laws with significant variations. State water quality control laws are more uniform, however, and follow a pattern set by federal legislation.

It is commonly held that waters arising within a state's boundaries are under the jurisdiction of the state. unless subject to powers reserved by the federal government. Consequently, as local customs developed and states were formed, each state adopted its own particular system of water law.

Surface water laws developed concerning two distinct philosophies which were consistent with the geo-climatic condition of the state. In the humid eastern half of the country and along the west coast, the riparian doctrine was adopted. The more arid western half of the country was faced with an immediate problem of deciding how to allocate a scarce resource and thus was compelled to develop a system of law peculiar to arid lands. The result of trial, error and compromise is the doctrine of prior appropriation. Some states have a varied water availability and concluded by adopting a mixed riparian/prior appropriation system. Despite the classification of state systems into three groups, there is a wide variation between states following the same doctrine as to the manner for determining water rights, exercise of the right, water use efficiency criteria, and system for obtaining water rights and administering and enforcing the law.

Ground water legislation occurred much later in the states due in part to the lack of knowledge of subsurface supplies and in part to adequate surface sources. The basic principles for use and control often followed the surface doctrines, but again each state adopted and modified the law to fit its perceived needs. Four different systems of control emerged.

The system of water law and administrative mechanism of these western states can be classified as "use-oriented" — the dominant objective being to utilize the water to produce an economic gain, which to many meant a livelihood and to others a profitable venture. The following discusses the important features

TABLE 1

A Summary of Western Water Law

Legal Feature / State	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Legal Feature / State
	WATER LAW DOCTRINES														
	Surface Water	Ground Water	Ownership	Evidence of Water Right	Basis of Allocation	Criteria of Allocation	Preference of Use (Order)	Date of Priority	Appurtency	Water Rights Registry	Water Quality In Right	Forfeiture of Rights	Drainage Rules	Basin of Origin	
1-ARIZ	P.A.	R.U.[2]	Puulic	Permit	B.U.	B.U.	1-2-3-4-5	D.O.A.	Strict	Original	Case	5 yrs	C.E. & C.L.[8]		1-ARIZ
2-CAL	P.A.& R.	C.R.	People	Permit	B.& R.U.	B.& R.U.	1-2--	D.O.A.	Unlimited	Current	Case + Statute	3 yrs	R.D.	Yes	2-CAL
3-COLO	P.A.	P.A.	Public	S.W.- decree G.W.- permit	B.U.	B.U.	1-2 over 5	S.W.- 1st step G.W.- D.O.A.	None	Original (Computerized)	Case	--[7]	C.L. (modified)	Yes	3-COLO
4-IDA	P.A.	P.A.	State	License	B.U.	1cfs./ 50 a.	1-2[4]	D.O.A.	Unlimited	Current (Limited)	Case	5 yrs	C.L.		4-IDA
5-KAN	P.A. + R.[1]	P.A.	People	Permit	B.U.	1 to 2 a.' /a.	1-2-5-6-3	D.O.A.		?	Case + Statute	3 yrs	C.L.		5-KAN
6-MONT	P.A.	P.A.	State	Permit	B.U.	1 miners" /a.	None	D.O.A.		Original (Limited)	Case	--[7]	C.E.		6-MONT
7-NEB	P.A. + R.[1]	R.U.[2]	Public	Permit	B.U.	1 cfs/70a. or 3 a.' /a.	1-2 over 5	D.O.A.		?	Case	3 yrs	C.E.	Yes	7-NEB
8-NEV	P.A.	P.A.	Public	Permit	B.U.	Conditions & Needs	None	D.O.A.		Original	Case	5 yrs	C.L.		8-NEV
9-N.M.	P.A.	P.A.	Public	Permit	B.U.	B.U. & good agr. practices	None	D.O.A.		Original	Case	4 yrs + 1 yr after notice	C.L.		9-N.M.
10-N.D.	P.A.	P.A.	Public	Permit	B.U.	1 cfs/80 a.	1-2 & 5-6	D.B.U.		?	Case	3 yrs	R.D.		10-N.D.
11-OKLA	P.A. + R.[1]	P.A.	--	Permit[3]	B.U.	B.U.	none	D.O.A.	Strict	Current	Case	7 yrs	R.D.	Yes	11-OKLA
12-ORE	P.A. + R.[1]	P.A.	Public	Permit	B.U.	B.U.	1-2-4--	D.O.A.	Strict	Original	Case	5 yrs	C.L.		12-ORE
13-S.D.	P.A. + R.[1]	P.A.	People	License	B.U.	1 cfs/70a. or 3 a.' /a.	1--	D.O.A.		Original	Case	3 yrs	C.L.		13-S.D.
14-TEX	P.A. + R.[1]	A.O.	State	Permit[3]	B.U.	B.U.	1-5-2-4-3-7-6	D.B.U.		Current	Case	10 yrs	C.L.	Yes	14-TEX
15-UTAH	P.A.	P.A.	Public	Permit	B.U.	Nature of Use	1-2	D.O.A.		Current	Case	5 yrs	C.E.		15-UTAH
16-WASH	P.A. + R.[1]	P.A.	Public	Permit	B.U.	Reasonably Necessary	None	D.B.U.		Current (Computerized)	Case + Statute	5 yrs	C.E.		16-WASH
17-WYO	P.A.	P.A.	State	Permit	B.U.	1 cfs/70a.	1-5	D.O.A.	Strict	Original	Case	5 yrs	Undecided		17-WYO
	P.A.=Prior Appropriation R.=Riparian A.O.=Absolute Ownership R.U.=Reasonable Use C.R.=Corrective Rights [1]All new water by P.A. [2]Lack comprehensive ground water laws			[3]Different types [4]In mining districts, 4 over 2 & 5 [5]Complex, see text	B.U.=Beneficial use. B.& R.U.=Beneficial & Reasonable Use		[1]Domestic & Municipal [2]Agricultural (irrigation) [3]Power [4]Mining [5]Mfg. & Industrial [6]Recreation [7]Navigation	D.O.A.= Date of application D.B.U.= Date of beneficial use	Strict= can transfer but criteria established Limited= water right for specific parcel, but transferable	Original= Initial filing recorded Current= User must notify Agency of name, use, place, etc., transfers unlimited		[6]All state recognize loss by abandonment [7]10 yrs is evidence of abandonment	C.E.= Common enemy C.L.= Civil Law R.D.= Reasonable Discharge [8]C.E.= flood waters C.L.= natural flows		

and status of the law of water allocation and use in the western states, summarized by Table 1.

SURFACE WATER LAWS

As previously stated, the seventeen western states have adopted one or both of the basic water law systems found in the United States. The system adopted by every western state is the doctrine of prior appropriation, with those states on the western seaboard and from North Dakota to Texas also employing the riparian doctrine to lands adjacent to watercourses. There is a definite trend to eliminate the riparian doctrine as demand on surface waters increase. For all practical purposes, most of the states with both doctrines have relegated the riparian system of surface water control to an insignificant role. However, a brief explanation of the doctrine's salient points will enable the reader to recognize the attitudes and drawbacks in efforts to control the quality of irrigation return flows.

Riparian Doctrine

Those states in the West applying the riparian doctrine follow the American Rule of Reasonable Use. Under this rule, riparian landowners can divert a reasonable amount of water with respect to all other riparians on the stream; and nonriparian lands may, under certain conditions, make a reasonable use of remaining waters.

Nature of the Riparian Water Right

Waters in states following the riparian doctrines are a public resource, held in trust for use by the people of the state. Thus, a landowner whose land borders a stream does not have an ownership right to the waters of the stream, but rather has a fundamental right by virtue of his land location to a reasonable use of the water and to be free from unreasonable uses of others that cause him harm (*Rancho Santa Margarita v. Vail*, 11 Cal. 2d 501, 81 p. 2d 533, 1938). He is essentially a correlative co-user with all other riparians on the water source and as between riparian uses, priority of use does not establish priority of right in times of decreased flows (*Pabst v. Finland*, 192 Cal. 124, 211 P.11, 1922). Consequently, his right to the use of water is not a right for a fixed quantity of flow or volume, but rather is dependent largely upon the extent of development that has taken place.

Manner of Allocation

Fundamental to the riparian law is the location of land on a water source. Although this requirement has been relaxed in many eastern states to permit use of water on nonriparian lands — as between riparians and nonriparians — water will first be allocated to the riparian landowner. Among the western states, California remains the one state in which the riparian right doctrine has major significance. In California, a riparian right can only be established upon riparian land. And, if a portion of the land to which a riparian right attached is severed from the original parcel, and itself does not have access to the watercourse or the riparian right is not specifically reserved for the portion, then the right is lost and cannot be restored.

More important to the allocation of water under this doctrine is the requirement of reasonableness in use, since the right does not consist of a definite quantity of water.

The reasonable use requirement limits the use of water to that quantity reasonably required for a beneficial use and prohibits waste or unreasonable use, or unmeasurable methods of use, or diversions (Const. of Cal., Art, XIV, Section 3).

Other rules on allocation and exercise of riparian rights include restrictions against transfer of riparian rights to nonriparian lands, water cannot be stored for later use under a riparian right (*Moore v. California-Oregon Power Co.*, 22 Cal. 2d 725, 140 P.2d 798, 1943), nor can foreign waters be claimed under a riparian right (*Crane v. Stevinson*, 5 Cal. 2d 387, 54 P.2d 1100, 1936).

Preference of User

Under either the natural flow or reasonable use theory, there is a preference for the "natural wants" over all other uses. The "natural wants" include household and limited livestock needs and have generally placed domestic-called uses in a preferred position. As between other uses — agricultural, industrial, recreational, etc. — there is no clear preference, but rather the courts have looked upon the reasonableness of use to determine conflicts between these uses.

Nonuse and Misuse of Rights

Riparian water law does not require a landowner to use the water in order to maintain the right in good standing. Unless the right to use water from an adjacent water source has been sold or transferred to other lands or uses, the right will continue as long as the land and water is continuous. Abandonment of water right is nonexistent under riparian law. There is a possibility, however, that a riparian who does not object to the open and notorious use by another, through prescription, may have his right reduced or lost.

Misuse of the right may result in a restriction on use and/or judgment for damages to those adversely affected. Parties injured through the misuse must assert their claim in court.

Statutory Modifications

There have been a number of significant recent changes in the water law of the riparian states primarily brought about by the inability of existing water supplies to meet the expanding demands on one side, and a recognition of public interest in water resources on the other.

The changes can be summarized into two major components: 1) establishment of a permit system to allocate water among certain users; and 2) creation of administrative machinery to assess water resources through the permit system.

Among the western states, the modifications to the original doctrine are strongly influenced by the simultaneous application of the doctrine of prior appropriation, increased demands on surface supplies for in-basin as well as out-of-basin use stimulated in part by large-scale reclamation projects, and heavy reliance upon ground waters in some states, i.e., California, Nebraska, Oklahoma, and Texas. In all of the dual-doctrine states except California, all new claims to the use of surface waters must comply with the statutory requirements of the prior appropriation doctrine. Since the 1967 Water Rights Adjudication Act in Texas, all surface water rights are now required to be filed, approved and administered by the Texas Water Rights Commission. All riparian right claimants are to file their claim with the Commission, or the right would be extinguished (T.C.A., Section 5.301 to 5.341). If the Commission desires, it may also adjudicate these claims.

Similarly, in Washington, under the 1967 Water Right Claims Act, riparian right claimants must have their claims adjudicated in order to protect their interests against holders of appropriation rights (W.R. C. §90.54.010). In California, if a suit involving the determination of water rights is brought in the superior court, the court can refer the case to the State Water Resources Control Board for a determination of *all* water rights in the stream system (C.W.C. *§2000 and 2001; C. W.C.* §2500 to 2900 sets out the procedure).

Regarding Irrigation Return Flow

The riparian doctrine has as an inherent component, the requirement that a riparian user make a reasonable use of the water and his right shall not be impaired in quantity or quality by the unreasonable use of another riparian. Thus, in theory, if the upstream riparian's return flows were degrading the quality of the water used by a downstream riparian, the latter has a basis for judicial redress. It must be pointed out that under the riparian system, an administrative structure for allocation and regulation of water does not exist (except in those western states where riparian claimants are required to file their claim or obtain a permit) and, thus, the injured party must rely upon his remedies in the courts through a private lawsuit.

The evolution of this doctrine was a fortunate event for it proved as useful for agriculture as it was for mining. As mining became more competitive, many miners and newcomers to the area began farming. The doctrine protected the first settler to use water on his land. Later settlers had to respect the prior ownership of land and the amount of water which the prior settler was using. Hence, the clique "first in time, first in right" symbolized most everything the early water users were concerned about.

The system that emerged was simple and direct. Although there are many variations between the appropriation doctrine states, a number of key principles exist to establish commonality, if not relative uniformity, among the states. These principles are:

1. There had to be a division from a natural stream or body of water. This has been relaxed in most western states during the last decade to allow in-stream use for recreation and fish and wildlife protection.
2. The water must be applied to a beneficial use. Initially, this was defined in constitutions and/or statutes to be domestic, municipal, stock watering, irrigation, and

certain industrial and power uses. Some state laws, like Wyoming, reflect the economic influence of one sector over another, i.e., the railroad uses were preferred to agricultural uses. In most of the western states, however, the rural representation insured agriculture a high position as a beneficial user. Beneficial use also referred to the nature of use, but will be discussed later.

3. When these two acts were completed, a water right was created. This right entitled the holder to continued use so long as the use was beneficial. The attributes of this right are discussed later.

4. Every water right acquires a priority date such that priority of right and not equality of right is the basis for distributing water.

The Water Right

The entire system of prior appropriation is based upon and evolves around the allocation of water under the concept of the water right. Simply put, this doctrine creates the right of private use of a public resource under certain conditions, which use has been declared to be a public use. The right does not automatically exist by virtue of the presence of water upon, flowing through, or under land. In all western states, these waters (some exceptions) are declared to be the property of the public, people, or state (see Column 3, Table 1). Regardless of whether the state or the public (people) own the water, the courts have held the state as a trustee to the public for the proper allocation and distribution of water and granting and protecting the right to use the water so allocated. Wyoming law states, for example:

> A water right is a right to use the water of the state, when such use has been acquired by the beneficial application of water under the laws of the state relating thereto, and in conformity with the rules and regulations dependent thereon (W.S.A. §41-2).

In Colorado, the Supreme Court very early in the state's history announced a rule that can be found in every statutory or judicial law of the other appropriation doctrine states. The famous *Coffin v. Lefthand and Ditch Co.* was decided in 1882 and held:

> . . . water in the various streams thus acquires a value unknown in moister climates. Instead of being a mere incident in the soil, it rises when appropriated to the dignity of a distinct usufructory estate or right of property . . . the right to property in this country by priority of appropriation thereto, we think it is and has always been the duty of the national and state governments to protect (6 Colo. 443).

The right so acquired has two legal characteristics. First, the right itself is a real property right. It is an exclusive right, which like other property interests, can be defined, is valuable and can be sold, transferred, mortgaged, or bequeathed. But the right differs from the right that attaches to land or chattels, for it is only a right to *use* the resource. Thus, it is called a usufructory right (see *Coffin* case above and O.S.A. 82 §105.2 as examples of judicial and legislative holdings).

The second characteristic is that since it is only a usufructory right and can only be exercised when the water authorized for diversion under the right is available and can be put to beneficial use, there is no absolute ownership in the corpus of the water prior to diversion. This water is still a public resource, and if the right holder cannot put it to beneficial use, he must allow it to flow past his point of diversion to other appropriations. However, if he can appropriately use the water, that water which is diverted into his delivery system is his personal property until it returns back to the stream or escapes his control.

The water right under the appropriation doctrine consists of several defining elements that give it value, dependability and security to the holder. The right:

- exists to a definite source of supply, e.g., specific river, lake, or ground water acquifer;
- is for a fixed and stated maximum quantity divertable;
- has a definite point of diversion to which conditions are to be maintained as of the time the appropriation took place;
- specifies the type of use for the diverted water;
- identifies the place of use (for application in the case of irrigation);
- implies the annual time of use based upon type and place of use; and
- assures the holder of at least an implied protection to the maintenance of water quality necessary to carry out the pur-

poses for which the water was appropriated.

As was previously stated, one of the key principles to the prior appropriation doctrine is the "priority of right" that is granted a user over subsequent appropriation. It is most often the priority date, dependability of flow in stream and location of point of diversion that gives a water its value.

In most states, the priority date is the date the application for a water right is received by the state agency. Generally, an application must be filed with pertinent information relative to the user, use and source of supply. If the application is approved, the water right will normally have the priority of the date of application (Column 8, Table 1). If the use requires construction of diversion, storage and delivery works over a period of years, the right, if the application is approved and notice to proceed given, will still retain the date of application when the water actually is put to use, through operation of the "doctrine of relation back." If, however, the applicant does not construct the works within the time period acceptable to both parties, and the delay is unexcusable, the right may have a priority beginning on the date the water is put to use.

Several systems were developed by the states to allocate water and provide evidence of water rights, including posting a notice at the point of diversion and filing a record with the county clerk. The predominant approach now is the permit system (Column 4, Table 1). An application is filed with the appropriate state agency who then takes the procedural steps of evaluating and determining its disposition. If approved, a permit is issued which may contain conditions of use. If denied, the applicant may appeal the administrative decision to the court. In some cases, the finalized water right may be called a license or certificate.

A few states have different classes of permits which greatly enhance their ability to allocate and regulate the use of water among competing interests. In Texas, there are eight classes of permits:

- regular permit — year-round perpetual right;
- seasonal permit — portion of calendar year (irrigation season and perpetual);
- temporary permit — short-lived specific use, no longer than 3 years;
- term permit — fixed number of years and expires;
- contractual permit — authorizes an appropriator to contract the use of his water to another for a term;
- permit under Section 5.141 — authorizes impoundment on nonnavigable stream on permittees' own property of less than 200 acre-feet and use for any specified purpose;
- storage permit — storage of water for project;
- emergency permit — allows emergency appropriation for not more than 30 days for public health, safety and welfare (T.W.R.C. Rule 129.02.05.001-.008).

Oklahoma has two broad categories of permanent and non-permanent. The former is subdivided into regular and seasonal, while the latter is divided into temporary and term (O.W.R.B., Rule 350). All states grant direct flow and storage permits. Colorado is the only state that does not have public representation in the water right allocation process. Water rights applications are submitted to the appropriate Water Court (one water court in each of the seven water divisions). Through a statutorily defined process, the Court and its referee act upon the application by giving notice through newspaper publication to water users in the area and holding hearings so protests to the application can be heard. If the application is acceptable, the Water Court will issue a decree as evidence of the water right. A conditional decree may be issued if the work to complete the diversion and put the water to beneficial use is to take place over a period of time.

One of the frustrating problems to water administrators and planners and often costly to water users under the current high demand for water and increase in sales and transfer is the recordation of water rights. The majority of states have a registry of the original issued water rights (Column 10, Table 1) which identifies the original appropriation, point of diversion, source of supply, amount divertable in continuous flow, or total volume terms, and type and place of use. In all states, any change or transfer in place or type of use and point of diversion must be approved by the state agency. This is primarily to protect other appropriators who may be adversely affected by the transfer if conditions of the stream and return flow are not accounted for. But, few states actually maintain a current registry of water rights that reflect current ownership. These statutes, or adopted regulations requiring notice to the agency of all ownership changes. Oklahoma and Texas have a computer card type report form that right holders must submit annually with pertinent data concerning ownership, amount of water diverted, and what uses were made of the resource. In some cases, failure to notify the state agency of ownership and other changes is prima facie evidence of non-use and could lead to forfeiture or abandonment. The burden of notice is usually placed upon the current owner. Even in many of these states, however, the current listing is not complete.

In the past, the purely engineering concerns of source, diversion point and type of use may have been sufficient to distribute water, that is, water could only be diverted out of a fixed and definite headgate. But, with problems of increased demand on the available supplies and the present need to resolve such water quality problems as those stemming from irrigation return flows, greater efficiencies in use must be achieved. This can, and in many cases are, being brought about by: 1) transfer of right to use water to higher value uses; 2) some voluntary action by water users to improve the diversion and delivery structures and locations; and 3) tighter administration of the conditions of water use granted a water right holder under the law. To effectively administer these laws (beneficial use and non-waste provisions), carry out water planning and development, and even take full advantage of transfer characteristics inherent in the property right in water, accurate records of *current* ownership and use are required.

One last feature of a water right for irrigation use must be mentioned. In all states of the West, when a water right is granted for irrigation use, the right becomes appurtenant to the land(s) described in the permit, that is, it attaches to those lands and cannot be used elsewhere without approval of the state agency (or Water Court in Colorado). Many variations as to the extent of attachment exist, however. Most states use what, for lack of a better term, we call limited attachment. This only requires approval of the state agency when proper measures and adjustments are made in the transfer to prevent impairment of other users' rights. In a few states like Colorado, the water right does not necessarily transfer with the sale of land (*James v. Barker*, 99 Colo. 551, 64 P2d 598, 1937).

In a minority of other states, the appurtenancy rule is strict. That is, the transfer can be approved if for uses other than irrigation (A.R.S., §45-172), or if it becomes impracticable to use the water economically or beneficially on the original lands (in re *Determination of Relative Rights to Use of Waters of Pantona Creek*, 45 Ariz. 156, 41 p2d 288, 1935). Wyoming applies the appurtenancy rule only to direct flow rights, but as noted by Meyers and Tarlock (1971, p. 528), some fourteen statutory exceptions riddle the principle. The other states with strict provisions on transfer are Oklahoma, Oregon, Nebraska, Nevada and South Dakota. The reason for many states tying water rights to land at the turn of the century was to prevent some of the fraudulent land and water sale practices that had gone on under earlier federal settlement schemes in the West.

Basis and Criteria of Allocation and Use

Beneficial Use

The cornerstone of water allocation under western water law as it has evolved is that beneficial use is the basis and measure of the right to use water. This is often the extent of definition found in the majority of western states water law (e.g., A.R.S. §45-101; N.R.S. §533.035; S.D.L.§46-1-8; W.S.A. §41-2). Thus, in order to use water, it must be taken for a beneficial purpose. This has evolved into the position that not only must water be used for a beneficial purpose, but beneficial use is the limit of the right (*Farmers Highline Canal and Reservoir Co. v. Golden*, 129 Colo. 575, 272 P2d 629, 1954). Usually the term "beneficial use" is not defined per se but is decided on a case-by-case method. It has two aspects, referred to above, that complicate the concept even more. Water is allocated to a beneficial use, so for that reason, many statutory provisions list types of uses recognized as being beneficial. Among the uses recognized as beneficial are: irrigation, domestic, power production, municipal, industrial, recreation and minimum flows for aquatic life. This short list is not meant to be comprehensive but, rather only to illustrate the spectrum recognized.

The other aspect is the use of the water itself must be beneficial and carried out in a beneficial manner. On this point, several states have elaborated the definition to provide directly to the administration of the laws. In California, the use of water is subject to the constitutional requirements that such use:

> . . . shall be limited to such water as shall be reasonably required for the beneficial use to be served, and such right does not and shall not extend to the waste, or unreasonable use or unreasonable diversion, of water (Cal. Const. Art. XIV, Sec. 3).

Texas applies this broad but more defined approach to beneficial use also. It requires that no more water be allocated and used than that amount "economically necessary for the purpose authorized when reasonable intelligence and reasonable diligence are used in applying the water to that purpose" (T.C.A., Sec. 5.002).

New Mexico law directs itself to irrigation specifically by placing a limitation on all rights by instructing the State Engineer not to allow the diversion of more water for irrigation than can be used consistent with good agricultural practices to produce the most effective use of water (N.M., Sec. 75-5-17).

Washington similarly addresses the use of water by agriculture. Its laws provide that an appropriator will be provided that quantity of water reasonably necessary to irrigate his land, but this irrigation is to be accomplished by the most economical method of artificial irrigation according to the methods employed in the vicinity where the land is situated (R.C.W., Sec. 90.03.040). The most economical method is to be determined by the court.

The concept of reasonableness is playing an increasingly more important role in appropriation states. For example, it may no longer be reasonable to irrigate a crop by flooding when another method, readily available, will produce crops as well or better and simultaneously save some of the water. Thus, even though the use — irrigation — is beneficial, the method of application is not reasonable.

Duty of Water

In addition to the requirement that water will be allocated to a user for a beneficial use, most states have adopted criteria to be followed in allocating water to agriculture. This criteria is commonly referred to as the statutory duty of water. To quote from the Supreme Court of Colorado:

> It is that measure of water, which by careful management and use, without wasteage, is reasonably required to be applied to any given tract of land for such period of time as may be adequate to produce therefrom a maximum amount of such crops as ordinarily are grown thereon. (*Farmers Highline Canal and Reservoir Co. v. Golden*, 129 Colo. 575 at 584, 270 p2d 629, 1954).

The majority of states incorporate this into their determination of the amount to be granted the water right applicant. But several states have quantified the duty. Little uniformity exists indicating the different conditions found in the states. Idaho, Wyoming and North Dakota allow 1 cfs per 50, 70 and 80 acres, respectively. South Dakota and Nebraska also allow 1 cfs per 70 acres but no more than 3 acre-feet per acre. Montana allows 1 miners inch per acre and Kansas varies between 1 to 2 acre-feet per acre, depending upon the circumstances (Column 6, Table 1).

Provisions in Nevada are particularly important to the subject of this report. In Nevada, the State Engineer is to consider the duties of water established by court decrees or by experimentation in the area where the water is to be used (N.R.S., §533.070). He is also instructed to consider the growing season, type of culture, and reasonable transportation losses. This flexibility allows the State Engineer to be precise in allocating water.

Waste

The corollary to beneficial use of water is the duty not to commit waste of water. This requirement is expressed by statute or court decision in all the western states. However, it must be stated that as what constitutes beneficial is difficult to define except on a case-by-case approach, it is equally difficult to categorically state what amounts to waste. In the analysis of case law by Hutchins, Elles and DeBraal, they note that an appropriator need not take extraordinary precautions to prevent waste if it is a reasonable use of the water according to the customs of the community (citing: *Joerger v. Pacific Gas and Electric Co.*, 207 Cal. 8, 273 P.1017, 1929), so long as the custom does not involve unnecessary waste of water (Hutchins, Vol. 1, p. 498).

Many states have statutory provisions like that found in Arizona (A.R.S. §45-109) and Nevada (N.R.S. §533.460) which prohibit waste and charge the party so committing waste to the detriment of another to be guilty of a misdemeanor.

Preferences and Priority to Use

These are two concepts in the appropriation doctrine that are often intermingled and confused in use of the terms. Priority of right has been described above as the *date of a right* that distinguishes it from *all* other rights for purposes of distribution of available water supplies in the source from which the appropriation is attached. This enables the senior right holder to demand and receive his allocation at the time the senior places a call for his water before the junior is entitled to exercise his. During low flows or scarcity, diversions are shut-off in inverse order. Hence, the value of an early water right.

Preferences, however, do not address a date of appropriation, but rather the *type of use* that receives preferential treatment by laws. In many states, certain types of uses are placed in an order establishing their preferred position (see Column 7, Table 1). This has two primary purposes. The first, in the allocation of water between competing, simultaneous applicants, the allocating agency can use the criteria that as between the applicants for supply of water insufficient to meet the needs of all, the applicant requesting water for a preferred use can be granted his right over those requesting water for a lower or non-preferred use.

The second aspect of the preference system is that during periods of scarcity, the preferred use has a *right* to exercise the condemnation power to obtain water from non-preferred uses. In all states but Texas, compensation must be paid. Texas has an "absolute preference" system which provides municipalities with the right to take water without compensation. As a practical matter, this is rarely if ever utilized.

GROUND WATER CONTROL SYSTEMS

Four Doctrines

Ground water resources are beginning to play a major role in agricultural, municipal and industrial water use. Approximately one-fifth of the water withdrawn in the country comes from this source.

Laws controlling the extraction and use of ground water have become as complex as surface water doctrines. Basically, however, the states apply one of four doctrines — absolute ownership, reasonable use, prior appropriation, or correlative rights (see Corker, 1971). Column 2 of Table 1 identifies the doctrines adopted by each state. A thorough treatment of ground water laws up to 1970 can be found in Hutchins (1974).

Absolute Ownership

The doctrine of absolute ownership had its origin in the United Kingdom with the 1843 decision of *Acton v. Blundell* (152 Eng. Rep. 1223.1843). Simply stated, the doctrine holds that a landowner can withdraw any water from beneath his land without liability to his neighbors resulting from such action.

Among the western states, only Texas has retained this rule. In Texas, the rule applies only to percolating waters and not subterranean streams or tributary stream underflows. But the presumption is that all ground water is percolating, thus allowing a landowner to take and use or sell all the water he can capture from beneath his land (*Texas Water Plan*, 1968). In areas where a defined acquifer exists, landowners can organize into a ground water conservation district and establish location, depth, discharge, and use rules (T.C.A., §7880).

Reasonable Use

Due to the extreme position of ground water use without liability as proclaimed under the absolute ownership doctrine, many states began modifying the laws into what has become known as the "American Rule of Reasonable Use." This change is synonymous to the modifications in the surface riparian doctrine. The rule of this doctrine is: since the rights of adjacent landowners is similar and their enjoyment in the use of ground waters is dependent upon the action of other overlying landowners, each landowner is restricted to a reasonable exercise of his own rights and reasonable use of his own property, in view of the similar rights of others (*Mecker v. E. Orange*, 77 N. J.L. 623, 74 A.379, 1909).

Among the two western states that have retained the reasonable use doctrine (Arizona and Nebraska), Arizona holds that one landowner can withdraw ground water, even though some harm is dealt his neighbor, if he is making a reasonable use of the water on land from under which the water is taken (*Bristor v. Cheatham*, 77 Ariz. 227, 255, P.2d 173, 1953), while Nebraska will allow out-of-basin diversions for municipal use if no damage is done to overlying landowners in the area where the water is extracted (In re. *Metropolitan Utilities District of Omaha*, 179 Neb. 783, 140 N.W.2d 626, 1966). It appeared that Arizona was leaning toward the Nebraska rule in the Jarvis cases (*Jarvis v. State Land Department*, 456 P.2d 385, 1964 and *Jarvis v. State Land Department*, 479 P.2d 269, 1970), with little limitation. Then, in early 1977, the court held in *Farmers Investment Co. v. Bettery, et al.* (558 P.2d 14) that water cannot be transported out of a basin if other overlying landowners are injured by the withdrawals. It is also important to note that neither state has yet adopted a comprehensive ground water code.

This doctrine leaves much speculation as to what is "reasonable use," but on the other hand, affords some measure of protection to property now existing and greater justification for the attempt to make new developments (*Katz v. Walkinshaw*, 141 Cal. 116, 74 P.766, 1903).

Correlative Rights

The doctrine of correlative rights in ground water originated in California and is a further refinement to the reasonable use concept. Several states originally adopted this doctrine, then changed to another rule (i.e., Utah), but now only California, among the western states, applies this rule. The doctrine holds that among landowners overlying an underground water supply, each landowner can make a reasonable use of that supply so long as the source is sufficient. But when the supply becomes insufficient due to the drought or draw-down effect, each landowner is entitled to water in proportion to the percent of his land in relation to all other lands overlying the underground waters *(Katz v. Walkinshaw, supra).* The net effect is to provide great flexibility of ground water use in an effort to maximize the resources, while providing equitable allocation when shortages occur.

Prior appropriation

Most of the western states found little reason to differentiate their systems of law for surface waters and ground waters. As a consequence, they adopted ground water statutes of a similar philosophy stating that this source should be allowed maximum development with recognition and protection given prior users. This does not imply, however, that surface water law was automatically applicable to ground water. In fact, several states enacted laws to control ground waters as late as mid-1950's and 1960's.

The rule provides that ground water is subject to appropriation for beneficial use providing the intended user complies with the statutory requirements, obtaining a permit or license as the case may be. The administrative official must determine if unappropirated ground water exists and what adverse effects would occur from approving the application.

In most states, the law allows the state water official, upon a determination that a particular ground water basin needs close management of withdrawals, to classify the area as a critical or designated ground water basin (see Colorado or New Mexico laws). When this occurs, the users are placed under direct control for the protection of the aquifer and vested rights.

DRAINAGE

The rights of landowners to protect their property from diffused surface waters is only incidental to the irrigation return flow quality problem, because most agriculturalists are concerned with how they can capture and use their source of supply. However, a brief explanation of the rules is considered useful in light of the growing awareness and ability of meeting different plant requirements for moisture and the need to adopt conservation practices which prevent erosion and lead to sediment control.

The three rules are: common enemy rule, civil law rule and reasonable use rule. Under the common enemy rule, diffused surface waters are considered an "enemy" of the landowner and he can construct dikes, drains or other necessary steps to protect his land from the damaging effects of the surface waters *(Tillinger v. Frisbie*, 138 Mont. 60, 353 P.2d 645, 1960; *Gillespie Land and Irrigation Co. v. Gonzalez*, 93 Ariz. 152, 372 P.2d 135, 1963, as regards to flood waters).

The civil law rule holds just the opposite. It is "essentially a rule of natural drainage holding that lower land is burdened with a natural easement of drainage in favor of higher land" *(Colorado v. Brannon Land and Gravel Co.*, 534 P.2d 652, Colo. App., 1975). However, the higher land cannot increase the burden of the lower land, and the latter can, if necessary, take protective measures to prevent damage to his land from unreasonable discharges *(Harper v. Johannesen*, 84 Ida. 278, 371 P.2d 842, 1962).

The third rule is in between the two previously discussed rules and basically holds there can be a reasonable interference with the natural flow of water by either party to protect their property (*Iven v. Roder*, 431 P.2d 321, Okla., 1967). See Column 13, Table 6-1 for the rules as adopted by the western states.

INCENTIVES AND DISINCENTIVES TO EFFICIENT USE

Basin of Origin

Several states have adopted rules to protect the water needs of landowners and populations within a watershed from future shortages caused by out-of-basin diversions and uses. California adopted a county of origin rule in 1931 (C.W.C. §10505) and a Watershed Protection Act in 1933 (C.W.C. §11460 to 11463). These provisions give a general protection to inhabitants within the county and basin to reclaim water in the future if needed from non-county or basin uses. The impetus to the Watershed Protection Act was the California Water Plan which has proceeded in spite of the reservations for future use within the basin.

Colorado and Nebraska also have limitation on exportation of water from a natural basin (C.R.S. §37-45-118(IV); and N.R.S. §46-206 and 46-265). In the case of Colorado, the law requires projects that use water out of the natural basin shall not impair present and prospective uses of water for irrigation and other beneficial consumptive use purposes within the natural basin, nor increase the cost at the expense of users within the basin.

Texas and Oklahoma have taken a different approach to out-of-basin diversions. In Texas, water for transfer out of the basin is restricted to those waters which will be surplus to the reasonably foreseeable water supply requirements within the basin of origin for the next 50-year period (T.C.A. §8280-9). In 1972, Oklahoma enacted the Stream Water Use Act (O.S.A. 82§105). It protects the current water users within a stream system from damaging out-of-basin transfers by requiring the Texas Water Resources Board to review the water needs in the area of origin every five years (*Ibid.*,§105.12).

Rights and Duties to Return Flows

Return flows are an important source of water in the arid western states, and as such are considered by water users and administrators as a commodity that should not be dealt with lightly. As water rights to natural flows were granted, the streams began to be augmented from seepage, tailwater runoff and percolation. Subsequently, other water rights were granted based upon this source of water and junior in time. As such, the courts have generally held that junior appropriators can rely on these return flows and protect their rights in this source (*Boulder v. Boulder and Left Hand Ditch Company*, 557 P.2d 1182, Colo., 1977; *East Bench Irrigation Co. v. Desert Irrigation Co.*, 2 Utah 2d170, 271, P.2d 449, 1954).

Also as a general rule, irrigation districts can recapture return flows before they leave boundaries and reuse these waters (*Ide v. United States*, 263 U.S. 497, 1972). But, this rule normally does not extend to individuals as return flows are considered by the courts to be the non-consumptive uses of water that returns to the stream from the proper and beneficial application of water.

This leaves a fine line between waste water and return flow. In *Binning v. Miller*, the Wyoming Supreme Court stated a rule common to many jurisdictions that one can recapture his waste water on his property and reuse it thereon (55 Wyo. 451, 102 P.2d 54, 1940). Other jurisdictions have gone on to say that a downstream user can appropriate waste water, but cannot compel the person committing the waste to continue to discharge nor prevent him from adopting improved practices that eliminate the waste (*Wedgworth v. Wedgworth*. 20 Ariz. 518, 181 P.952, 1919).

Loss of Water Rights

Water rights under appropriation doctrine can be lost through misuse. There are four ways in which this may occur.

The first is abandonment. Should a right holder not use his right for a statutory period of time and intend not to use it, his water right may be lost. The important element is intent, but this may be difficult for the state or party claiming abandonment to show. The state or another user must bring action against the user and prove both elements. Abandonment rules exist in all the western states.

The second is forfeiture. This is a statutory remedy to nonuse and only requires a showing of nonuse of all or a part of the right for a specified period of time. Automatically after the statutory term (usually three or five years), the water reverts to the public for appropriation by another (see Column 12, Table 1). There are variations in state laws as to notice and procedures for carrying out the forfeiture provisions.

Adverse possession is the third method, and this occurs when another openly and notoriously uses the water right of a person, and that person does nothing about it. If this continues for a specific period, the former can claim the right as his own. The practice is not looked upon with great favor by the courts, however.

Condemnation is the fourth major type. This occurs when a preferred user or public entity exercises the right of condemnation. Normally the only real issue is the amount of compensation. Colorado, however, recently passed a law requiring municipalities condemning agricultural water rights to show the necessity for taking such action (C.R.S. §138-6-201 to 216; see Radosevich and Sabey, 1976).

Water Quality in Water rights

There is at least an implied right of water quality in the water right under the doctrine of prior appropriation. In only two states (California and Washington) do the statutes make specific provision of the element of water quality in a right, such that a user can make the same demands on an agency to protect his interest in water quality as he can his interest in the quantity he is entitled to according to the priority of right.

In all the western states, the courts have recognized the common law doctrines of nuisance and trepass as applying to the protection of property interests in water. Most of the cases surround the discharge of mine tailings into a stream and subsequent injury to downstream agricultural users. An example of the nature of cases, as they pertain to agriculture, is the Idaho decision *Ravndal v. Northfork Placers*, 60 Idaho 305, 91 P.2d 368 (1939). In that case, plaintiff's ditches and crops were injured by the hydraulic mining process employed by the defendant mining company. The Idaho Supreme Court affirmed the damage judgment awarded by the district court and held that:

> Numerous authorities announce the doctrine that while a prior use of the water of a stream for mining purposes necessarily contaminates it to some extent, such contamination or deterioration of the quality of the water cannot be carried to such a degree as to inflict substantial injury upon another user of the waters of said stream (*Ravndal v. Northfolk Placers*, 60 Idaho 305, 91 P.2d 368, 1939).

In spite of this result, one law review article has stated that private nuisance actions have "provided virtually no incentive to the offenders to reduce their harmful discharges into the waterways" (Wood, 1971).

The conclusion from an analysis of all the cases studied to date on the water quality protection issue is that a water user must pursue his own remedy in court if he wishes to protect the quality of water he is receiving.

WATER QUALITY LAWS IN THE WEST

Water pollution control has actually had a long history in the United States, dating back to the local laws for sewage control in the colonial times. By 1948, when the first significant piece of federal legislation was enacted, most states throughout the country had adopted some form of pollution control legislation. State and local health departments were responsible for carrying out the law. There was little activity between the federal and state governments up to that point, for no federal program existed. The federal attitude was that pollution control was primarily a state responsibility. In fact, this view prevailed until 1965 when the federal government declared it would initiate control where states failed to adopt standards and enforcement procedures (Water Quality Control Act of 1965, P.L. 89-234).

At present, all of the western states have established water pollution control laws that are highly uniform. The legislative enactments and promulgations of rules that have taken place in the past four years have been primarily to qualify for grants under the Water Pollution Control Act as amneded and to adopt a permit discharge system comparable to the federal NPDES permit program.

The pattern of present state water quality control legislation is very similar to the components and declarations found in P.L. 92-500. As a general statement, the state acts consist of five components:

1. Water quality policy
2. Criteria for pollution control.
   a. classifications of waters
   b. water quality standards

   c. effluent discharge standards
3. Control activities.
   a. permit system
   b. construction grants and programs
   c. public participation in planning and setting of standards
4. Sanctions and enforcement measures.

Water Quality Control Policy

The foundation of water quality control within each state is found in policy declarations introducing the legislation, or in pronouncements by the agency charged with administering the law. Fifteen of the states have policy statements which are very similar.

Typical of the water policies found in the other states is the statutory provision contained in Oregon's law:

> (1) To conserve the waters of the state;
> (2) To protect, maintain and improve the quality of the waters of the state for public water supplies, for the propagation of wildlife, fish and aquatic life and for domestic, *agricultural*, industrial, municipal, recreational and other legitimate beneficial uses;
> (3) To provide that no waste be discharged into any waters of this state without first receiving the necessary treatment or other corrective action to protect the legitimate beneficial uses of such waters;
> (4) To provide for the prevention, abatement and control of new or existing water pollution; and
> (5) To cooperate with other agencies of the state, agencies of other states and the Federal Government in carrying out these objectives (O.R.S. §468.710, emphasis added).

As a general proposition, the policy declaration also contains specific reference to the protection of beneficial uses of water as provided in the water allocation laws, nondegradation of waters that exceed current water quality standards and target dates identical or close to those found in federal legislation. The specific policy of Idaho's Board of Health and Welfare towards water quality is "to provide for an orderly and economically feasible comprehensive water pollution control program, which program shall be administered to conserve the waters of the State for all legitimate beneficial uses, including uses for domestic purposes, agriculture, industry, recreation and fish and wildlife propagation" (*Water Quality Standards and Wastewater Treatment Requirements*, Idaho Dept. of Health and Welfare, June 1973).

Other provisions found in state laws and policy statements formulated by the agencies of importance are the salinity policy of Arizona (A.W.Q.S. Rules R9-21-103), emphasis upon soil erosion control and programs of Kansas (K.S.A. §2-1902) and Arizona (A.R.S. §45.2001), and recognition by Colorado that the problem of water pollution in Colorado is closely related to the problem of water pollution in adjoining states (C.R.S. §25-8-102(1)). California is concerned over ground water quality (C.W.C. §12922) and waste water reclamation (C.W.C. §13510). Many states have policies for water quality control in their environmental acts.

One of the most important declarations as far as irrigation return flow is concerned is that found in Montana's recent act. The law states that it is the public policy of the state of Montana to:

> (a) conserve water by protecting, maintaining and improving the quality and potability of water for public water supplies, wildlife, fish and aquatic life, agriculture, industry, recreation and other beneficial uses;
> (b) provide a comprehensive program for the prevention, abatement and control of water pollution (R.C.M. §69-4801(1)).

The section further states that "it is not necessary that wastes be treated to a purer condition than the *natural* condition of the receiving stream as long as the minimum treatment requirements are met." "Natural" refers to conditions or material present from runoff or percolation over which man has no control *"or from developed land where all reasonable land, soil and water conservation practices have been applied.* Conditions resulting from the reasonable operation of dams at the effective date of this Act are natural" (*Ibid.*, §2, emphasis added). As a general rule, however, agricultural return flows are included in the definition of "pollutant" in the state laws.

Criteria for Water Quality Control

Three district criteria for control of water quality are usually found in state laws. They are classification of waters, water quality standards and effluent discharge standards. A few states also have set pretreatment standards (i.e., South Dakota) and performance and toxic effluent standards (i.e. Nebraska and Wyoming).

In most every state, the water quality control agency is directed to classify the state waters and develop and maintain a comprehensive program for prevention, control and abatement of water pollution. Except for New Mexico and Oregon, all the states have developed a classification system based upon the beneficial uses of water. These systems range from 2 to 14 classifications, but in general, include domestic water supply, full body contact recreation, fish, wildlife and other aquatic life protection, agricultural and industrial, and aesthetic uses. Often, special provisions in the classifications are made for perennial and non-perennial streams, streams designated for no future discharge, as return flow streams or streams requiring advanced waste discharge.

In California, the regional water quality boards are to develop a classification scheme according to the particular regional needs. New Mexico has not developed a classification scheme but instead has chosen to regulate water quality according to specific geographical areas with water quality standards adopted for the various river basins. Oregon has not adopted a classification system for water quality control.

In conjunction with classification of state waters, all states have developed water quality standards according to bio-chemical composition that is to be protected or limits not to exceed. The typical approach is to develop general and specific standards with various parameters. The parameters for general standards vary in number from 6 to 15.

Indicative of the parameters for specific standards are those found in Idaho:

A. Coliform Concentration
B. Dissolved Oxygen
C. Hydrogen Ion Concentration
D. Temperature
E. Turbidity
F. Total Dissolved Solids

> (*Water Quality Standards and Wastewater Treatment Requirements*, Idaho Dept. of Health and Welfare, §VIII, June 1973).

Several states have specific reference to irrigated agriculture in their water quality standards. Arizona requires their Water Quality Control Council to consider, among fifteen other items:

> 16. In formulating any applicable standard pertaining to agricutural irrigation and drainage waters, the Council shall be guided by the principle that such waters are put to beneficial use within the state for the irrigtion of lands or become return flows to the waters of the state and subsequently reused, and that such standards shall not diminish the water available for such uses nor deprive the state of such water (A.R.S. §36. 1857 A).

The above statute further commends the Council to:

> 1. Not require any present or future appropriator or user of water to divert, cease diverting, exchange, cease exchanging, store, cease storing, or release any water for the purpose of controlling pollution in the waters of the state.
> 2. Exclude from water quality standards wholly private waters closed to all public uses and not discharging into or polluting any other waters of the state (A.R.S. §36.1857 B).

South Dakota has adopted specific water quality parameters for irrigation waters. The specific areas covered by these regulations include specific levels of coliform and fecal coliform organism, total dissolved solids, conductivity and sodium absorption ratios (S.D. Surface Water Quality Stats. Ch. 34:04:02:43, 1975). The criteria for irrigation waters is applicable only from May 15 to September 30, Also, the criteria for coliform and fecal organisms is applicable only to water used to irrigate root crops.

All western states have also adopted waste discharge standards, but have very little reference to irrigation return flows.

Control Activities

There are basically three control activities employed by the western states water quality agencies to carry out the policies and criteria discussed above. They are: 1) permit system for effluent discharges; 2) construction grants and programs; and 3) planning and development with public participation in setting various standards for water quality control. These tools are not to be confused with the legal tools for enforcing the law against violators, such as cease and desist orders and judgments.

The only activity to be discussed here is the permit system. The construction grants and programs do not directly apply to irrigated agriculture; at least there has been little if any use at the state level. The planning activities are in conjunction with the federally developed and promoted 208 planning and other planning activities required by federal law.

A permit is required from the state water quality agency to lawfully discharge or emit wastes into the surface waters of the state. Each state has particular requirements and conditions for obtaining a permit. The conditions normally consist of four, but may vary from state to state. They are:

1. Effluent limitations;
2. Schedule of compliance and interim dates;
3. Special conditions; and
4. A monitoring program if appropriate.

The usual activities requiring a permit include:

1. Discharge of any wastes into the waters of the state from any industrial or commercial establishment or activity or any disposal system;
2. Construct, install, modify or operate any disposal system or part thereof or any extension or addition thereto;
3. Increase in volume or strength of any wastes in excess of the permissive discharges specified under an existing permit;
4. Construct, install, operate or conduct any industrial, commercial, or other establishment or activity or any extension or modification thereof or addition thereto, the operation or conduct of which would cause an increase in the discharge of wastes into the waters of the state or which would otherwise alter the physical, chemical or biological properties of any waters of the state in any manner not already lawfully authorized;
5. Construct or use any new outlet for the discharge of any wastes into the waters of the state (O.R.S. §468.740).

Most permits are for a term of five years with renewal if the permittee is still in compliance with the conditions set out in the permit and if other conditions have remained unchanged. Permits can be modified or terminated if: a) the permittee violates the conditions of the permit; b) the permit was obtained by false or misrepresentation or failure to fully disclose all relevant facts; or c) physical conditions change in the receiving waters that require either a temporary or permanent reduction or elimination of the permitted discharge.

The permit programs of ten western states have received EPA designation to administer the entire NPDES process, that is, to issue new permits, reissue expired permits, monitor permit compliances, and enforce violations (*Water Quality*, 1976, p. V-19). Table 2 identifies the states accepted by EPA to implement the NPDES program, and the reasons the remaining states have not received designations.

Sanctions and Enforcement Measures

The intent of federal and state water pollution control laws is to prevent and abate discharges which are harmful to the public health and welfare and the beneficial uses to which water is put. In so doing, the various laws have described or granted administrative authority to determine what activities must be stopped because of immediate harm, what discharge limits will be tolerated or excluded from control under certain conditions, such as discharges into non-perennial streams, and what discharges require a permit and compliance to an abatement and limitation schedule. Many of these points have been discussed above.

However, beyond a doubt, the sanctions which allow certain discharges under permitted or excluded conditions do not constitute the bais for a *right* to discharge. To dispel any notion that a discharge requirement is in the nature of a permit to discharge, the Porter-Cologne Act specifically provides that discharges do not receive the status of vested rights, but are in the nature of a privilege (C.W.C. §13267(c)).

One of the major problems and complaints of pre-1972 state and federal water pollution control legislation was the lack and inability of enforcement of the law by the regulatory agencies. The problem was two-fold. First, the legal mechanism was lacking or too weak. A polluter could "beat" the agency in court. Second, where the legal procedure was adequate, the penalties were often so small or minor that it "paid" to pollute rather than incur the cost of pollution control. Also, political and economic interests often got in the way of effective enforcement.

TABLE 2

Status of NPDES Delegation in the 17 Western States*

EPA Regions	*Accepted*	*Reason for EPA Non-Acceptance*
Region VI		
New Mexico		Legal
Oklahoma		Legal
Texas		Legal
Region VII		
Kansas	6-28-74	
Nebraska	6-12-74	
Region VIII		
Colorado	3-27-75	
Montana	6-10-74	
North Dakota	6-13-75	
South Dakota		Resources
Utah		Legal
Wyoming	1-30-75	
Region IX		
Arizona		Legal
California	5-14-73	
Nevada	9-19-75	
Region X		
Idaho		Legal
Oregon	9-26-73	
Washington	11-14-73	

*Status as of February 1, 1977, Update to Table V-5, p. V-21, *Staff Report to the National Commission on Water Quality*, April 1976.

As a result of P.L. 92-500, the enforcement provisions are mandatory, not discretionary, and the legal tools are more precise. In all the state laws and regulations examined, the state water quality control agencies now have a host of approaches with varying degrees of impact. The range begins with notice to the polluter and an opportunity to voluntarily comply with the law. This may be done by submitting a detailed plan and time schedule to come into compliance.

If the discharger fails to respond to this administrative notification or directive, the agencies have four other direct actions that can be taken. They are:

1. Issuance of a regulating order, commonly referred to as a cease and desist order.

2. Initiation of court action to obtain a restraining order and/or injunction to prevent further discharges.

3. Levying of civil penalties.

4. Initiation of criminal proceedings by the county or district prosecutor or state attorney general.

Several states also permit the state agency to expend monies to clean up the waste (California) or restock fish killed (Nebraska) and charge the violator with reasonable costs.

REGULATIONS AFFECTING IRRIGATION RETURN FLOW QUALITY

There has been very little legislative or agency rule-making activity by the seventeen western states in the specific area of irrigation return flow quality control up to this time. Only three states have adopted regulations impacting the quality of these return flows. They are California, Idaho and Nebraska, with Idaho's Department of Health and Welfare adopting regulations requiring a permit to discharge from *large* irrigation projects only within the past few months (*Environment Reporter*, Vol. 7, No. 42, p. 1610, Feb. 18, 1977). These regulations have been recently repealed by the Idaho State Legislature.

North Dakota has adopted regulations pertaining specifically to salinity but not to irrigation return flows generally (*Standards of Surface Water Quality State of North Dakota*, Section VII, North Dakota State Department of Health, 1973). South Dakota has promultated water quality standards that include reference to irrigation return flows. Oklahoma has adopted regulations for return flow streams and mixing zones, but not specifically for the source of pollutant from irrigated agriculture.

In most states, irrigation return flows are ignored, exempted, or subject to qualifications in the application of control regulations. The Water Quality Control Council in Arizona may make a determination that water quality standards do not apply when the entire flow in a watercourse that would otherwise be dry is effluent from agricultural irrigation return flow (*Arizona Water Quality Standards*, R9-21-210A). Furthermore, water quality standards do not apply to the collection, return, or drainage of agricultural irrigation return flows, excess or tailwaters to canals, laterals or other manmade irrigation water delivery facilities within an irrigation system, or chemical maintenance of irrigation facilities within an irrigation system where agriculture is the only designated primary beneficial use, or physical or mechanical maintenance of irrigation facilities within an irrigation system. But, the law of Arizona does make it unlawful for any person "... to discharge any agricultural, irrigation or drainage waters into waters of the state and thereby reduce the quality of such waters below the water quality standards established therefore by the Council in violation of an order issued pursuant to Section 36.1854" (A.R.S., Section 36.1858).

California applies a unique approach to handling the irrigation return flow problem. First of all, irrigation return flow is not treated as a point or non-point source. It is simply looked at as a water quality degradation problem. The state is divided into various regions. Each region has the authority to control the water quantity and water quality within its region. The State Water Resources Council Board must adopt guidelines which set forth minimum standards for the disposal of wastes (Calif. Regs., Section 2555), and each Regional Board develops its own system of regulations to comply with the NPDES.

Monitoring programs must determine the quality and quantity of supply waters entering agricultural areas and return flows from agricultural areas entering streams and/or receiving waters. A monitoring program may be carried out under permits which have been issued to agricultural areas for either two or five-year periods.

Planning programs are initiated by the Regional Administrator or the State Board upon the advice of the Agricultural Water Quality Advisory Committee. Through the planning process, agricultural discharges which can be controlled by a permit are to be identified and permits issued. These programs must develop the best management practices for agriculture which will reduce pollutant loads to surface waters, and develop policies or guidelines for individual farm operations and basin-wide management problems. The California approach to meeting EPA's requirements of issuing permits for irrigation return flows as a point source is to identify all entities within an irrigation system or subsystem from which discharges can be identified and monitored, and have these entities cosign the permit. This satisfies EPA and enables the state to decentralize monitoring and management to the local entities while retaining control and enforcement if necessary.

In Colorado, a permit is not required for any flow or return flow of irrigation water unless a federal act or regulation so requires (C.R.S., Section 25-8-506).

Idaho did accept the designation of irrigation return flows as point source discharges, but has not been delegated by EPA to carry out the federal NPDES program.

Although Montana has no specific regulations pertaining to irrigation return flow, the policy of the state strongly implies that action will be taken to protect receiving streams from *runoff or percolation* where unreasonable land, soil and water conservation practices have been applied.

A number of states have retained regulations adopted prior to the decision of *N.R.D.C. v. Train* (1975) which were based upon the original regulations promulgated by EPA (Idaho, Nebraska, Nevada). These regulations exempt irrigation return flows except if the return flows are from lands of more than 3,000 acres or 3,000 non-contiguous acres discharging into the same drainage systems. This exemption was struck down in the N.R.D.C. case and the states are merely waiting for new federal regulations before amending or trying to carry out the existing ones.

Summary

As complex as the water law systems are in the West, any situation taxing the ability of current water supplies to meet increasing demands will require changes in the laws. The constraints to improved management lie primarily in the water rights laws, and as a general proposition, it is concluded that these laws:

- lack specificity in definition, inhibiting implementation of concepts such as beneficial use and waste prevention
- provide an ad hoc approach to resolving key water problems through the courts
- insure that the property right concept in water will continue to be the most single critical roadblock to curative solutions
- recognize customary standards of the community as the criteria for beneficial use
- fail to require the adoption of a recordation system to assist in implementation of legally enforceable concepts and programs for improved water management

- fail to integrate water quantity and quality control, conceptually and administratively
- provide disincentives for recapturing or properly using return flows, or salvaged and excess waters by prohibiting transfers to other lands or users.

To systematically attack the water management problem and particularly the return flow quality problem, changes in state laws must include:

- efforts to achieve uniformity within state laws and administration
- efforts to achieve workable uniformity in the laws between states
- development of criteria for efficiency in water allocation and use according to key principles of:

  a) beneficial use

  b) waste

  c) duty of water

  and apply this criteria to all uses, private and public

- recognize and promote the "public trust" of water agencies and the public duty in the user for use of public resources
- incorporate, specifically, the element of water quality in a water right
- shift to a term permit or periodic evaluation of effective water use
- adopt a program of influent control which includes outflow analysis with criteria to determine the degree of improvement relative to needs and opportunity costs.

An Influent Control Approach to Irrigation Return Flow Quality Management

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ABSTRACT

The Influent Control Approach is based upon the assumption that improved water management plus improved agricultural practices will significantly contribute to improved water quality, and the conclusion that best management practices plus best agricultural practices will provide irrigation return flow quality control, which in turn will contribute significantly to the national goal of cleaner water through improved water quality.

The Influent Control Approach consists of eight specific components: (1) designate areas for irrigation return flow quality management and designate the responsible area entity; (2) develop standards and criteria for beneficial use in designated areas; (3) introduce incentives to use water more efficiently; (4) include the element of water quality in new or transferred and changed water rights; (5) adopt and enforce a reporting and recording system for water rights; (6) recognize reasonable degradation from agricultural water use; (7) adopt an Agricultrual Practices Act; and (8) promote close cooperation or integration of state water agencies and related functions.

PHILOSOPHY AND CRITERIA FOR EFFECTIVE CONTROL

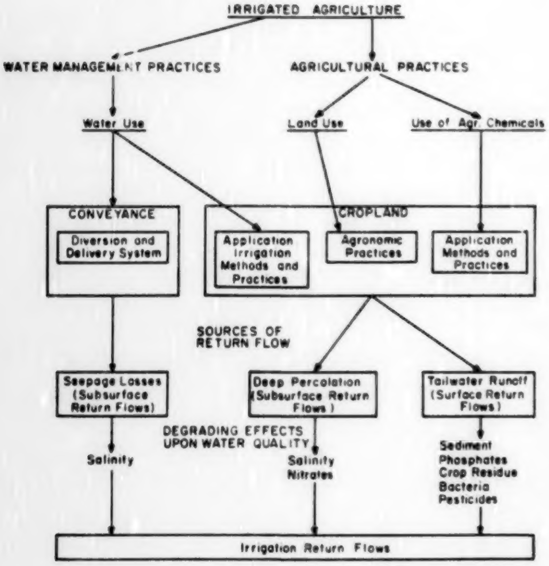
The Need

Water quality control from irrigation return flows has perhaps caused the greatest degree of disenchantment among state and federal personnel charged with carrying out water quality programs under P.L. 92-500 than any other category of pollution sources. Since the time that first regulations for irrigation return flows were promulgated in 1973, there has been strong and distinct differences of opinion among the various agencies dealing with water at both state and federal levels of government, and within their ranks as well. Many western states have called a stop to their programs until EPA adopts what the states consider a workable approach. The legal gyrations of the past four years have caused them to undertake minimum activity so as not to directly violate any particular law or regulation. Not one western state has completely and enthusiastically embraced a program of including irrigation return flows as a "point source" and thus subjecting all irrigation to the NPDES program.

Part of the problem for the disenchantment stems from the physical difficulties in dealing with the irrigation return flow quality problem where it does exist. Equally important is the lack of a philosophical foundation and thrust to resolving a problem of this immense complexity, as well as inherent resistance to control.

Viewing the problem from both the position of water users and agency personnel charged with controlling the problem, this study attempted to be both logical and pragmatic in formulating an implementable and sustaining approach to irrigation return flow quality control. The philosophy and criteria which follow are building blocks to the proposed Influent Control Approach (ICA) set out in this paper. It is the authors' opinion that awareness, not concurrence, is essential to an understanding and acceptance of a program.

The complex situation faced by public officials and water users is illustrated in Figure 1. To achieve the highly desirable goals of cleaner water called for by the Federal Water Pollution


IRRIGATED AGRICULTURE
WATER MANAGEMENT PRACTICES
AGRICULTURAL PRACTICES
Water Use
Land Use
Use of Agr. Chemicals
CONVEYANCE
Diversion and Delivery System
CROPLAND
Application Irrigation Methods and Practices
Agronomic Practices
Application Methods and Practices
SOURCES OF RETURN FLOW
Seepage Losses (Subsurface Return Flows)
Deep Percolation (Subsurface Return Flows)
Tailwater Runoff (Surface Return Flows)
DEGRADING EFFECTS UPON WATER QUALITY
Salinity
Salinity
Nitrates
Sediment
Phosphates
Crop Residue
Bacteria
Pesticides
Irrigation Return Flows

(Radosevich & Skogerboe 1977)

Figure 1. Impact of water management and agricultural practices upon irrigation return flow quality.

Control Act of 1972 (P.L. 92-500), it is necessary to realistically assess the specific nature and problems caused by surface and subsurface return flows from irrigated agriculture. Present water management and agricultural practices create irrigation return flows from the conveyance system and cropland that may have a degrading effect upon water quality in the receiving waters.

Philosophy

The proposed philosophy upon which to formulate a successful program for control of irrigation return flow quality consists of four interlocking propositions. First, the ultimate goal achieved by the federal and state agencies is improved water quality by way of improved water management, with this particular study focusing upon the return flow characteristics and problems of irrigated agriculture. In this context, improved water management means water quality enhancement through reductions in tailwater runoff, seepage losses, and deep percolation losses (i.e., surface and subsurface return flows, which are point and non-point sources, respectively).

Second, the program should promote social and economic well being through cooperative action. Every effort should be made to prevent polarization between state and federal agencies and local water user groups. An approach must be designated to stimulate a tripartite relationship between the water users and the state and federal agencies, while still maintaining the identity of each.

Third, only attack the problem after it has been realistically identified.

Fourth, voluntary compliance is more desirable than forced or involuntary compliance in implementing a management or control approach.

Criteria

Based upon this philosophy, the following criteria must be met for an implementable and sustaining program in irrigation return flow quality control:

1. The approach should result in improved water management practices specifically and improved agricultural practices generally. In the context of this paper, improved agricultural practices can be achieved through joint progress in two areas: (a) proper land use and (b) proper application of agricultural chemicals. As stated previously, water management includes affects upon the quantity and quality of surface and subsurface return flows.

2. The approach should prevent social disruption and polarization of water users (e.g., individuals, irrigation companies and water districts) and state and federal agencies. Maintaining separate identities is necessary, maintaining opposition is not. In most western states, water users have gone on record opposing past federal and state efforts to control irrigation return flow quality.

3. The approach should be palatable to water users. Some of the most often expressed concerns of the water users are: What is the problem and how significant is it; how am I involved; if I agree to a permit, what does that mean to me now, as well as potential control in the future (i.e., what rights and liberties am I giving up by agreeing to a nebulous program); what is it going to cost; what benefits will be achieved; and, who pays for nature's discharges?

4. The approach must be feasible, flexible and allow for state agency discretion in working with local entities. State agency concerns which must be met include: a

determination of the significance of the problem; ability to implement the program because of manpower limitations; identification of pollution sources; failure of past programs to include subsuface flows; credibility with water users; conflicts with other state agencies (e.g., water quality administration and agriculture agencies); and, the ultimate impact of such a program upon water quality, flow regime of streams and water users.

5. The approach should improve the credibility of state and federal agencies. Presently, most agricultural water users feel alienated against the federal and state water quality control agencies.

6. The approach should utilize existing institutions (e.g., laws and organizations) and accepted concepts (e.g., designation of problem areas such as critical ground water basins, beneficial use, and duty of water) as much as possible.

In order to implement any approach, both the water users and the agencies must have knowledge of the resources they are "managing." The irrigation system is too highly integrated and complex to be subjected to a frigid unilateral control program.

AN INFLUENT CONTROL APPROACH

Irrigation Return Flow Characteristics

Irrigation return flows have few characteristics which allow them to be viewed as a typical point source pollution discharge problem. Most pollution contained in irrigation return flow occurs as a natural process of diverting and using water for a legally appropriated beneficial use. But, the pollution often occurs beyond the boundaries of the control of the water user. Thus, the first distinct feature is *problem identification.*

Because the degraded return flows may be either surface or subsurface, and most often diffused rather than collected into a discrete conveyance system from the contribution source, the second feature is *contributor identification.* From a technological standpoint, contributor identification requires an evaluation of the sources of pollution; whereas, from a legal viewpoint, contributor identification requires a determination of *who* is polluting.

Allocation of water under western states laws requires that it be for a benefical use. Water allocated for irrigation is generally allocated to specific lands with the quantity based upon a fixed state-wide duty of water standard (e.g., 1 cfs / 70 acres in Wyoming, 2 acre-feet per acre in Nebraska).[1]

The right to use water is a property right to the holder, which is to be exercised according to priority with other users and availability of flow. Because there is no prorationing during shortages as under the riparian doctrine, and because this property right is one of rapidly increasing value in the West, the inherent incentive to the holder is to protect that right by diverting the full entitlement without regard to the fine line between beneficial use and waste. Thus, a third factor emerges, i.e., *law and customary diversion preempt equal weight to external diseconomies.*

The fourth feature gives rise to the proposed influent control approach described hereafter. This is *the correlation of input to output.* In addition to the possibility of controlling degraded return flows at their discharge, or effluent control, an impact can be exerted upon the quality of water discharged from irrigation uses by changes at the input stages, i.e., delivery and application of water. Because of the elusive nature of irrigation return flows, the traditional approach of effluent control is not considered adequate nor feasible in light of a more economic, simple and functional alternative within the control of the water user and influence of state water officials. That alternative is to control the influent. In the case of irrigation return flow, this includes water user discretion on the delivery and application of water (use of well known technologies such as canal lining to curb excessive seepage losses during conveyance, or improved irrigation methods and practices to reduce deep percolation losses and tailwater runoff), proper land use to retard or prevent erosion of soil and subsequent sediment pollution in tailwater, and proper application of fertilizers and pesticides.

These four features plus: a) the system of water quantity and quality administration at the state level, and b) the peculiarities of our judicial system, rules of evidence and burden of proof, require an approach which is both preventative and curative but within the parameters of a known demonstrated problem. Because end-of-pipe treatment is neither technically satisfactory, nor economically justifiable, the Influent Control Approach (ICA) is designated to get at the *cause*, not the consequence, of the problem and promote alternative solutions within the control and capability of irrigation water users generally. Where voluntary action to alleviate the known problem is not taken, existing laws for water quantity use and control of discharges by permit can be exercised.

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[1] In a few states, Nevada for example, discretion to determine quantity is given the State Engineer.

Theme of Influent Control Approach

The underlying theme of the ICA can be summarized as:

1. Proof before control
2. Proceed cautiously and positively.
3. Stimulate voluntary action based on demonstrated need to change.
4. Maintain relationship between agencies and water users.
5. Create or maintain credibility.

Assumptions

The Influent Control Approach is premised upon ten assumptions. They are:

1. Achieving the goals of P.L. 92-500, the Federal Water Pollution Control Act of 1972, and policies of federal and state laws to improve the use of our national resources is highly desirable;
2. The concept of property rights in water and other constitutional guarantees will be maintained;
3. The legal procedures of the judiciary and agencies will be utilized;
4. Improved agricultural practices and improved water management will result in improved water quality;
5. Irrigation return flow problems and appropriate solutions to these problems are *site specific;*
6. Water users (farmers) will respond when it has been demonstrated that there is a problem to which they are contributing;
7. Technical and legal solutions to identify problems must be appropriate and viable (technically sound, economically feasible, legally implementable, and socially acceptable);
8. Many irrigators will respond on a voluntary compliance basis;
9. Those users who do not respond will feel a local social pressure as a result of being "out-of-tune" with the newly evolved customs of the community; and
10. Regardless of approach, there will be some users who will not respond or will resist change, thereby requiring some mechanism for enforcement.

Influent Control Approach Components

As was alluded to above, the distinction of this approach to irrigation return flow quality control is to *indirectly* correct the unreasonably degraded discharges caused by irrigated agriculture by *directly* affecting the influent or input to the system. This approach is based upon the assumption that improved agricultural practices (IAP) and improved water management (IWM) will contribute to improved water quality (IWQ). In specific context of this paper, it is further conduced that best management practices plus best agricultural practices will provide improved irrigation return flow quality control (IRFQC), which in turn yields improved water quality.

$$\text{BMP} + \text{BAP} = \text{IRFQC} \longrightarrow \text{IWQ}$$

Because the nature of agricultural pollution from irrigation is too complex to rely upon end-of-pipe treatment, the cause of the problem is examined in its broader context, i.e., present water management and agricultural practices, with the emphasis upon only those elements of agricultural practices relating to or having an affect upon return flows. The concept of best management practices is currently employed by EPA and the states and refers here to improvements in local[2] water management. Best agricultural practices is used here to include proper land use and proper application of agricultural chemicals.

To reiterate, every effort in formulating this approach was made to decentralize the *act of control* to the lowest common denominator — the irrigator — because of his ability to voluntarily and directly impact the quality of return flows and because of a recognition that agriculturalists traditionally are independent people who prefer to be actors, not pawns. The components of the ICA thus provide: (1) the design and direction to irrigation return flow quality control; (2) the opportunity for voluntary compliance by water users in problem areas; and (3) the means to effectively assert involuntary compliance upon those contributing to the problem who refuse to adopt better practices by the responsible government agencies.

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[2] Local is used to distinguish water quality control within the irrigation system or subsystem from state and national control.

The Influent Control Approach is designed to improve water quality by reducing excessive seepage, tailwater runoff and deep percolation, reducing sediment in return flows through erosion control and reducing chemical concentrations in return flows through licensing and/or control resulting from over-application of pesticides and fertilizers. Since irrigation return flow quality problems differ from one irrigation system to another, the approach provides the latitude to introduce change and control according to the nature of the problem, without requiring unnecessary compliance by those irrigators outside problem areas.

Based upon this background, the Influent Control Approach (Figure 2) is designed with eight specific components. The first six components pertain to improving local water management, with components 1 and 2 having application in the problem area only and components 3 to 6 having state-wide jurisdiction. Component 7 pertains to land use and chemical applications affecting water quality and has state-wide jurisdiction. Component 8 focuses upon the functional ability of agencies to carry out the program.

The Influent Control Approach consists of the following components to be carried out by the states:

1. Designate Areas for Irrigation Return Flow Quality Management and the Responsible Area Entity.

Action — Based upon monitoring and analysis for indentifying significant irrigation return flow problem areas within the state, the state agency will: a) designate the boundaries of the problem area, which may be the boundaries of an irrigation system or subsystem or watershed; b) designate an entity, i.e., legally constituted body representing water users within the area, to undertake responsibility for working with the water users, collecting data and disseminating information. The area entity may be a newly formed organization, an existing organization, i.e., irrigation district, that assumes the program or a federation of numerous existing organizations in the designated areas; and c) insure that the entity is carrying out the best management practices developed for this area, as well as best agricultural practices.

Rationale— Applying the designated area approach to controlling unreasonable degradation from irrigation return flow enables the state to focus only upon those areas within its boundaries where a problem has been identified. Thus, not all irrigators are depicted as shifting externalities (i.e., costs from use of degraded water) upon the public and downstream users; all irrigators regardless of how well they manage their water and land resources are not subjected to the time consuming procedures and implications of a permit system. Consequently, water users are not collectively polarized against the efforts of state and federal agencies to reduce and prevent water quality degradation. This first component is the corner-stone of the influent control program because it draws attention only to problem areas without the guilt insinuations or accusations that farmers are so sensitive to.

From a practical point of view, the area entity, which may be represented by an existing irrigation or water-related organization, would utilize a representative board of commissioners that would be responsible for carrying out monitoring, discussing ways to alleviate unreasonable degradation by irrigation return flows to receiving waters with water users in the designated area, and encouraging voluntary improvement of agricultural practices by those users identified as contributing to the area's problem. For those users (or entities representing those users within an area) who refuse or fail to respond as recommended, the area entity would notify the state water quality control agency of the specific non-compliance, and the state would then proceed under existing federal and state law to initiate control and enforcement that is, under the general provisions of

A SOLUTION:

An Influent Control Approach (ICA)

ASSUMPTION:

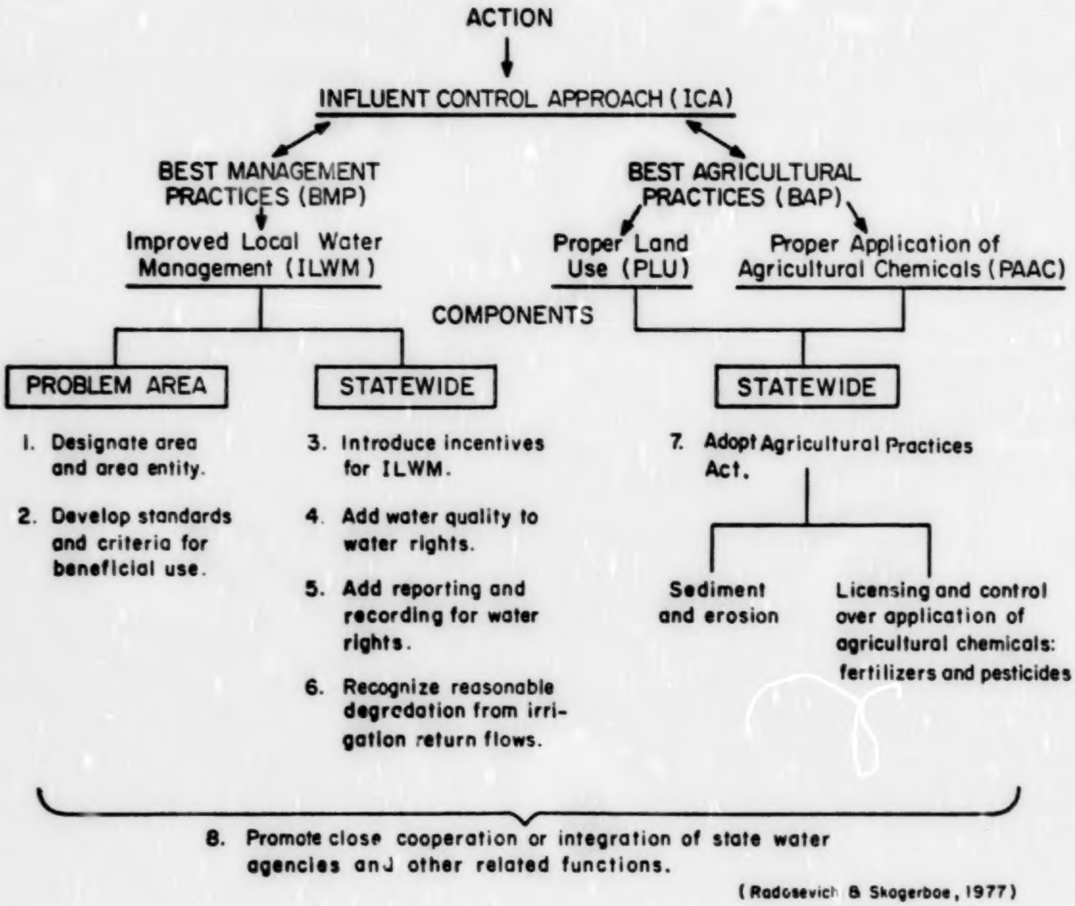
Improved Agricultural Practices + Improved Water Management = Improved Water Quality
(IAP + IWM = IWQ)

CONCLUSION:

Best Management Practices + Best Agricultural Practices = Irrigation Return Flow Quality Control
(BMP + BAP = IRFQC → IWQ)

DEFINITIONS:

BMP = Improved Local Water Management (ILWM)
BAP = Proper Land Use (PLU) and Proper Application of Agricultural Chemicals (PAAC)


ACTION
INFLUENT CONTROL APPROACH (ICA)
BEST MANAGEMENT PRACTICES (BMP)
BEST AGRICULTURAL PRACTICES (BAP)
Improved Local Water Management (ILWM)
Proper Land Use (PLU)
Proper Application of Agricultural Chemicals (PAAC)
COMPONENTS
PROBLEM AREA
STATEWIDE
STATEWIDE
1. Designate area and area entity.
2. Develop standards and criteria for beneficial use.
3. Introduce incentives for ILWM.
4. Add water quality to water rights.
5. Add reporting and recording for water rights.
6. Recognize reasonable degradation from irrigation return flows.
7. Adopt Agricultural Practices Act.
Sediment and erosion
Licensing and control over application of agricultural chemicals: fertilizers and pesticides
8. Promote close cooperation or integration of state water agencies and other related functions.

(Radosevich & Skogerboe, 1977)

Figure 2. Influent Control Approach to irrigation return flow quality management.

the water pollution laws, prohibiting discharges of pollutants and violation of stream standards. In these cases, the identified and non-complying irrigator discharge can be required to obtain a permit under the regular NPDES program. The area entity is thus responsible for assisting in managing the agricultural practices within the designated area, but control and necessary enforcement are appropriately left to the state.

Precedent — The concept of designated areas for resources control and management is well recognized and applied in many western states for ground water and municipal water supply. In most instances, water users participate on commissions or boards having jurisdiction over the management area.

2. *Develop Standards and Criteria for Beneficial Use in Designated Areas.*

Action — For each designated area within a state, the water quantity and quality agencies will collaborate to arrive at standards and criteria for beneficial use of water. Such standards and criteria will not constitute an impairment or taking of water rights, but rather be the technical limits of water delivery and application under the climatic, soil and othe agronomic conditions of the area. These conditions for water use would be tantamount to a calculated "duty of water"[3] for the area in light of the return flow quality problems.

Rationale — Under the water laws of each western state, water is allocated under the concept of beneficial use. This term is generally not defined, it is normally nebulous, but does in general meet the needs for both allocating and distributing water within the state. However, in certain areas due to soil characteristics and water use practices, irrigation return flow quality problems do develop which are directly related to the delivery and application of water. Within designated areas, it is necessary to develop specific standards and criteria for beneficial use that still comply with the concept of a water right under state law.

Precedent — Under Nevada water law, the State Engineer has discretion to determine the duty of water based upon the site specific characteristics of the irrigated area, the type of use to which the water will be put, and the impact upon surrounding water users. Utah is another state that has applied the variable duty of water concept in determining the appropriate amount of water to allocate under a water right. However, the state agency in Utah has had to proceed through a judicial determination. These two states are in contrast to the standard concept of duty of water found in many states — for example, Wyoming and Nebraska — in which a fixed duty of water has been adopted that is applicable statewide.

3. *Introduce Incentives to Use Water More Efficiently*. Historically, the Agricultural Conservation Program administered under the U.S. Department of Agriculture, with technical assistance provided by the Soil Conservation Service, has provided cost-sharing funds to farmers and irrigation districts for irrigation system improvements, most of which had water quality benefits. This program has been relatively inactive in recent years because of lack of funds. However, this program should play a very important role in the Influent Control Approach, as a part of the federal-state-local water users tripartite.

Action — Most western states have revolving funds or low interest loan programs for water resources planning and development. Generally, these programs require the applicant to be an irrigation district or other corporate body. Where such state programs exist, change in the legislation and/or regulations for participation qualification should be changed to allow: (1) individual irrigators to qualify; (2) broaden the use of funds to include on-farm improvement practices as well as improvement of delivery systems; and (3) include in the objectives of the program the improvement of water quality. When states have no such programs, a low or no-interest loan program containing the above three components should be adoped in order to cooperatively assist with the federal government and local water users in achieving improved water management and agriculture practices.

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[3] Duty of water means the quantity of water necessary for effective use for the purpose to which it is put under the particular circumstances of soil conditions, method of conveyance, topography, climate and crop grown (*Water and Water Rights*, Vol. 5, Sec. 408.2, 1972).

In addition, dissemination of information about other state and federal agency incentive programs should be carried out by the state water agencies, particularly to the designated management areas and cooperation extended to insure utilization of such programs.

Other incentive programs, which may require legislature enactments or agency regulations, could include encouragement of trading, leasing or selling of "saved" water from more efficient practices as an inducement to improve the delivery systems and methods of application. State or local water markets, under the direction of the State Engineer (or equivalent state office), could monitor or control the uses of these waters.

To counter the traditional attack against such an incentive program, it is highly conceivable downstream juniors would be the most likely to benefit, particularly if they were given priority to pay for this water.

Rationale — By providing incentives for water users in designated areas, the farmers will have an opportunity to voluntarily improve their water use practices, which in turn will result in improved irrigation return flow quality. This is consistent with the philosophy of encouraging voluntary compliance versus forced or involuntary compliance. Further, if states are to create standards and criteria for beneficial use, it is the opinion that some mechanism should be made available to the farmers that will facilitate compliance with the new criteria. Without it, irrigators are on solid legal grounds to continue exercising this water right as they have in the past. The legal cost to the state and water users to change this traditional practice may far outweigh devising a process and procedure by which water users can be encouraged to improve their efficiency in water use for both quantity and quality benefits, while still protecting the downstream users.

Precedent — Funds have been made available to irrigation districts and water users through the federal Department of Agriculture-Agricultural Conservation Program, with the Soil Conservation Service providing technical assistance. In addition, several states have state-wide programs in which low or no interest monies are made available to water users for improving their delivery systems. In Wyoming, the funds may be used for improving laterals and application practices.

4. Include the Element of Water Quality in New or Transferred and Changed Water Rights.

Action— The water quality element should be a general provision added to all new water rights and requests for extensions, changes in use and transfers, in order to provide the necessary authority to state water agencies for later setting and enforcing of numerical standards (either with respect to water application or return flows, or both). Where water quality standards on streams for beneficial use have been realistically set, such standards can be incorporated by reference to water rights from that source of supply.

This action may require legislative endorsement, but under the vast majority of state law, it is conceivable that agency regulations can initiate this component.

Rationale — The element of water quality is only implicit in western state water laws, with the exception of California which has made it an explicit element in all water rights since 1969. As a consequence, water users must normally rely upon common law doctrines and private litigation to protect their water right where the quality has been degraded to levels that hinder usage. Because the quality element is not explicit, as are the other elements of a water right — quantity, source, point of diversion, type of use, and place of use — the state agency charged with adminstration of the water laws and rights is not in a favorable position to initiate action to prevent harm from water quality deterioration, and thus the management capability extends only to quantity control.

Precedent — In California, there is a general provision (which is added to all new water rights, extensions on water rights, and changes in ownership or type of use) that the water will be used in such a manner as not to unreasonably degrade the usage of water for downstream users. In some instances, the State Water Resources Control Board has also applied numerical water quality standards to particular water rights.

5. Adopt and Enforce a Reporting and Recording System for Water Rights.

Action — Notice would be given to all water users and water right claimants to submit a report to the water right administrative agency indicating their name, address, basis for claiming right to use water, use of water, source and beginning data for water use. Water users may be given notice by publication in local newspapers. Many states have already initiated a "tabulation of water rights" program to acquire this data. It is necessary, however, to also adopt a system of annual reporting, indicating particularly changes in ownership since other material changes (e.g., transfer in type and place of use) require state approval.

Rationale — Although this component is more directly related to improving water management within the states rather than irrigation return flows only, it is related to the ability of the state to manage water quality because of the relationship between the diversion and application of water and the resultant return flow water quality. Most western states have inadequate knowledge of present ownership of water rights, and thus: a) have procedural difficulties in notifying water users of matters directly affecting their rights; b) are unable to effectively remove "paper water rights" from the records that are maintained and thus making forfeiture provisions in the law nearly useless; and c) would be hampered in incorporating the element of water quality to new, extended or changed water rights.

One of the major difficulties faced in attempts to control irrigation return flow quality is "contributor identification." A data base of who the water right holders are will greatly facilitate efforts to encourage implementation of best management practices and best agricultural practices.

Precendent — Both Idaho and Oklahoma have a system by which the current owners of water rights are required to submit to the state water right administration agency an annual report (in the case of Oklahoma, this is done on a computer card) which specifies who the users are, where the water is used, and approximately quantity. Failure to submit these annual reports serves as prima facie evidence of non-use and could lead to forfeiture of the water right.

6. Recognize Reasonable Degradation From Agricultural Water Use.

Action — Legislative recognition of this natural consequence of water use for irrigation purposes is needed at the state and federal levels.

Rationale — It is commonly accepted that any use of water for irrigated agriculture is going to result in some degradation of the quality of return flows. To pretend otherwise is to either continue a process of "playing the game" or will ultimately remove irrigated agriculture with its obvious adverse effects. Common knowledge knows the latter will not occur, but a tremendous and unnecessary cost to prove it could be extended upon irrigators and the public through the failure of legislatures to recognize natural processes of water use.

Precedent — New Mexico has adoped a specific provision in their statutes which states that ". . . reasonable degradation of water quality resulting from beneficial use shall be allowed" (NW Rec. Stat.§75-39-11).

Montana has arrived at the same conclusion by defining "naturally occuring conditions" in their water quality standards as those "present from runoff or percolation over which man has no control or developed land where all reasonable land, soil and water conservation practices have been applied" (MAC 16-2.13(10)-S14480, Water Quality Standards, § (3) Definitions). Several state supreme court decisions also recognize certain degradation from water use, e.g., *Ravndale v. North Fork Placers* (91 p.2d 368 Idaho, 1939) where some contamination from a mine will necessarily occur to a stream.

7. Adopt an Agricultural Practices Act.

Action — Many of the 17 western states have laws and programs requiring the licensing of agricultural chemical distributors and applicators with the state Department of Agriculture. The laws and/or programs should be revised or new legislation adopted to include the following:

a) Sediment and erosion control.

b) Licensing and control over application of agricultural chemicals to include pesticides and artificial fertilizers.

c) Creation of an Agricultural Practices Control Board consisting of representatives from the agriculture, water quantity and quality, soil conservation (if separate) and fish and wildlife agencies, and appointed members of the public. The board's functions would primarily be establishing rules, regulations and procedures for carrying out a) and b) above and insuring functional implementation through coordination and designation of duties to appropriate state agencies.

Rationale — Due to the impact upon water quality resulting from the application of herbicides, pesticides and fertilizers in the agricultural sector, and the inability of the state to control these practices, it is highly recommended that an Agricultural Practices Act be adopted which requires licensing and monitoring of distributions and applications of such chemicals and control over harmful land management practices contributing to erosion and subsequent sediment problems in receiving waters. There may be many other agricultural practices which could be included under such an act.

It is essential to recognize the interconnection between these activities and resulting water quality problems (which may in turn contribute to downstream and ground water supply problems) and the usual division of jurisdiction and duties between various state agencies. Short of complete reorganization of state agencies to insure interrelated activities all under one agency (which may not only be impossible but highly undesirable), an Agricultural Practices Control Board (APCB) consisting of action representatives from the various involved state agencies and members of the public could insure coordination and implementation of their rules and regulations. The current 208 planning bodies could be designated to assume local implementation.

Precedent — Again, California has led the way in licensing and monitoring of commercial applicators of herbicides and insecticides. Oregon has been considering the appropriateness of such an act to alleviate their major irrigation return flow quality problems. However, a comprehensive agricultural practices act has not been prepared in any of the western states. Iowa has adopted erosion control legislation that even authorizes imposition of a fine on those who fail to adopt approved practices.

8. Promote the Close Cooperation or Integration of State Water Agencies.

Action — To facilitate the implementation of the Influent Control Approach to irrigation return flow quality management, it is important that close cooperation and coordination exist between state water agencies through operation of a liaison board or committee, or integration of the state water agencies under one department.

Rationale — It is difficult to provide the necessary agency support to carry out any new program, but even more difficult to introduce a program of management and control over an area of activity highly sensitive to government intervention. In addition to adding duties to agencies often already burdened with heavy programs. efforts to control irrigation return flow quality meets with strong resistance from an inflexible and institutionalized system of property rights to the use of water in which the state water quantity agency often maintains a close relationship with the water users. The result is potential polarization between the state agency carrying out water quality control and the state water quantity agency.

However, because of the interdependence of water quantity and quality, particularly as a natural process in water applied to irrigation, it is inconsistent to promote the goals of P.L. 92-500 and not promote the coordination or integration of agencies charged with carrying out water quantity and quality control.

Precedent — In 1969, California combined the water quality and quantity agencies under the Porter-Cologne Act in order to specifically attempt to manage the resources in a rational manner. In 1972, Washington created the Department of Ecology which encompasses all three of the primary water functions; namely, water adminstration, water quality control and water resources development. Texas, Oregon and Kansas are comtemplating an integrated approach, while Oklahoma has chosen to utilize an advisory coordinating board to interface the various water activities of numerous state agencies.

EPILOGUE

Based upon discussions with state water quantity and quality personnel from all 17 western states, it is apparent that most states feel a real credibility gap exists between the Environmental Protection Agency and the State agencies; that in those states where the state agencies attempted to implement the federal program, a credibility gap developed between the water users and the state agency; and, in several states the personnel expressed the opinion that EPA let them down by backing off after they attempted to carry out a control approach they did not agree with in the first place. In nearly every state, the water user organizations and individuals have polarized to combat the imposition of uncertain regulation over their possible water use. A permit concept is nothing new to them and they know that eventual control can emanate from an initially harmless permit. For this reason, the current relationships between the three principals can be graphically described as shown in Figure 3. Missing are the prime ingredients of credibility and understanding. It is considered necessary:

1. that public officials responsible for carrying out laws appreciate the position of the water users and the nature of irrigated agriculture; and
2. that water users appreciate the water quality problems caused and the often awesome responsibilities and duties of the federal and state water officials in carrying out the legislative mandates.

If water users and state and federal agencies will embark upon a cooperative undertaking, a tripartite relationship can evolve that will instill credibility and achieve improved water quality. This would once again get those directly involved with water use and with administration of laws working together and not through advocates. The tripartite relationship (Figure 4) can develop if personal objectives and discipline orientations are not allowed to constrain a causal and flexible approach. A cooperative approach will facilitate the implementation of an action program.

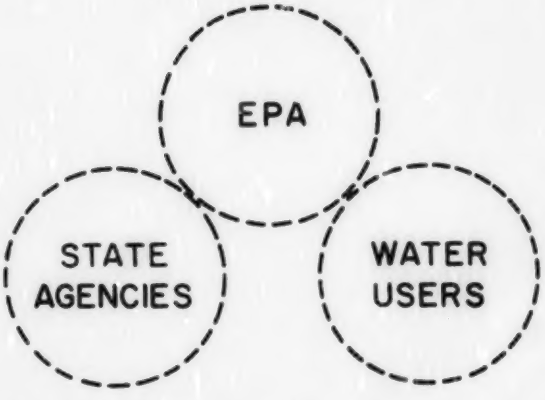


Figure 3. Polarization between water users and state and federal water quality agencies.

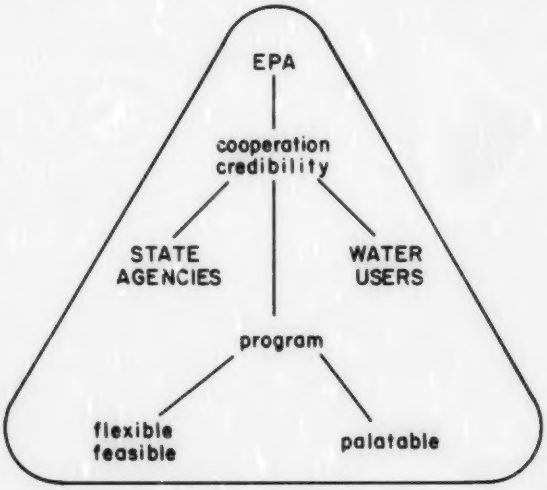
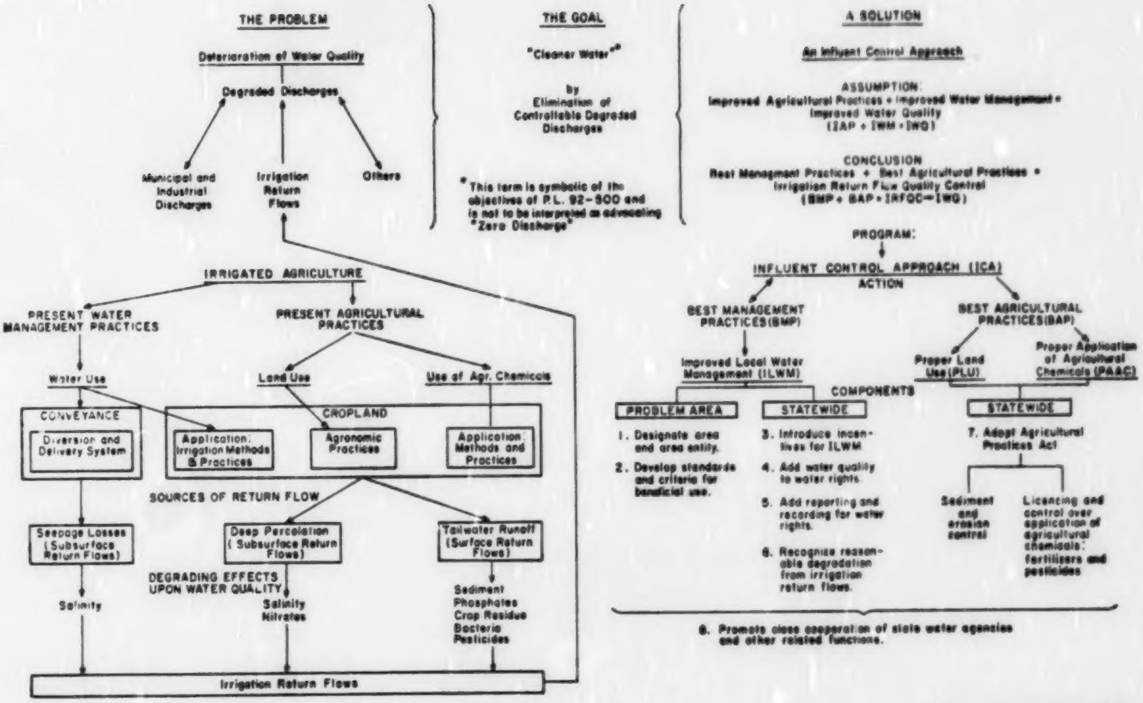


Figure 4. Tripartite relationship.

In Figure 5, the relationship between water quality problems resulting from irrigation return flows and the Influent Control Approach is shown. Irrigation return flows can be influenced to successfully eliminate controllable degraded discharges from irrigated agriculture and improve the quality of out nation's waters affected by such discharges. An Influent Control Approach is recommended based upon the conclusion that BMP + BAP = IRFQC ⟶ IWQ ⟶ Cleaner Water.


THE PROBLEM
Deterioration of Water Quality
Degraded Discharges
Municipal and Industrial Discharges
Irrigation Return Flows
Others
IRRIGATED AGRICULTURE
PRESENT WATER MANAGEMENT PRACTICES
PRESENT AGRICULTURAL PRACTICES
Water Use
Land Use
Use of Agr. Chemicals
CONVEYANCE
Diversion and Delivery System
CROPLAND
Application: Irrigation Methods & Practices
Agronomic Practices
Application: Methods and Practices
SOURCES OF RETURN FLOW
Seepage Losses (Subsurface Return Flows)
Deep Percolation (Subsurface Return Flows)
Tailwater Runoff (Surface Return Flows)
DEGRADING EFFECTS UPON WATER QUALITY
Salinity
Salinity
Nitrates
Sediment
Phosphates
Crop Residue
Bacteria
Pesticides
Irrigation Return Flows
THE GOAL
"Cleaner Water"*
by
Elimination of
Controllable Degraded
Discharges
* This term is symbolic of the objectives of P.L. 92-500 and is not to be interpreted as advocating "Zero Discharge"
A SOLUTION
An Influent Control Approach
ASSUMPTION:
Improved Agricultural Practices + Improved Water Management = Improved Water Quality
(IAP + IWM = IWQ)
CONCLUSION
Best Managment Practices + Best Agricultural Practices + Irrigation Return Flow Quality Control
(BMP + BAP + IRFQC = IWQ)
PROGRAM:
INFLUENT CONTROL APPROACH (ICA)
ACTION
BEST MANAGEMENT PRACTICES (BMP)
BEST AGRICULTURAL PRACTICES (BAP)
Improved Local Water Management (ILWM)
Proper Land Use (PLU)
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COMPONENTS
PROBLEM AREA
STATEWIDE
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1. Designate area and area entity.
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4. Add water quality to water rights.
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6. Recognize reasonable degradation from irrigation return flows.
7. Adopt Agricultural Practices Act
Sediment and erosion control
Licencing and control over application of agricultural chemicals: fertilizers and pesticides
8. Promote close cooperation of state water agencies and other related functions.

(Radosevich & Skogerboe, 1977)

Figure 5. Relation between the Influent Control Approach and water quality degradation from irrigation return flows.

A Process for Identifying, Evaluating and Implementing Solutions for Irrigation Return Flow Problems

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ABSTRACT

The purpose of this study has been to develop an effective process for implementing technical and institutional solutions to the problem of return flow pollution. The process developed is to: (1) define the problem in terms of its legal, physical, economic and social parameters, (2) identify potential solutions in relation to the parameters of the problem, (3) test the implementability of these potential solutions for diverse situations, and (4) specify those solutions or groups of solutions which are the most effective in reducing pollution and are implementable. This process is initially conceptualized in the paper and then the general results of its application to three study areas in the western United States are summarized.

INTRODUCTION

Water quality control has been a broad national objective since the enactment of P.L. 84-660, the Water Quality Act of 1956. However, from 1956 until the late 1960's, the emphasis has been almost entirely upon control of point sources of discharge from municipalities and industries. Obviously, these elements of pollution could be readily identified and various legal and economic measures could be designed to induce or compel elimination or reduction of harmful discharges.

Contrasted to this concern, three different conditions have produced a slow response by state and local officials with regard to agricultural pollution control programs. The first condition is the relative invisibility of non-point pollution. The second has to do with the more or less localized nature of the adverse effects from agricultural pollution and the difficulties of determing injuries in the absence of obvious outfalls. And, finally, it is only recently that a concerted effort by the federal government has been undertaken in tackling in some general way the problem of non-point pollution and in interpreting the provisions of a very complex law.

Thus, other than blatant violations (such as direct discharge of animal waste and chemicals into streams and rivers), control of pollution from agricultural activities has been noticeably lagging. In addition, agricultural uses of water are controlled by state agencies which, at least in most western states, are primarily concerned with water allocation, distribution and administration. In this respect, concern for beneficial use of water, duty of water use and wastages does not also include the degradation of return flows from overapplication or misuse of water.

Agricultural water quality control has recently become a substantive part of discussions among the various states in the West. Problems ranging from salinity and chemical degradation, sedimentation and other problems associated with suspended material have been examined predominantly from a physical control perspective and technologies have been developed which could alleviate or eliminate such problems.

An examination of the total quantity and diversity of nonpoint source pollutants, especially in the rural areas, indicates the complexity of the problem that must be faced. It is obvious that simply applying technological solutions is not going to solve the nation's water quality problems. Indeed, more and more it is recognized that many of the gains made in the point source area will not result in cleaner water because of the failure to act in controlling the highly significant non-point sources of pollution. (It is here that the NCWQ has highlighted the historical asynchrony that has developed between implementation of sections of the Act dealing with point source treatment alone — Section 201 — and point and non-point source management considered jointly — Section 208.) In addition, however technically feasible they may be, proposed solutions to problems of non-point pollution have been met with substantial resistance, despite economic and social analysis demonstrating the long-range benefits — local, regional and national — that would result from the mitigation or elimination of water quality degradation.

It is obvious that this problem is two-fold. On the one side, there is disenchantment with the physical difficulties in dealing with the invisible irrigation return flows wherever they exist. However, equally important is the lack of a basic agreement as to resolving a problem of immense complexity, namely the conflicting and competing goals, objectives and priorities of water resources management. At the same time, there are also a number of factors that influence the strategies for resolving this problem such as the level of environmental quality desired; the cost of achieving that quality; the equitable distribution of costs; the presumed benefits to be derived from enhancing environmental quality; and, finally, the means for achieving that quality, including the host of economic, legal, political, technical, as well as social constraints.

The emphasis of the present approach is to utilize existing technologies for improving water management and alleviation of salinity and sedimentation from irrigation return flows, and introduce institutional alternatives which will make possible implementation of a range of solutions per specific cases.

In the discussion, "institutions" are defined as those social mechanisms by which society organizes, manages and directs its affairs. "Institutional alternatives" are the whole range of legal, economic, political, and cultural institutions (or crystallized ways of doing things) which are used for meeting social needs. The purpose of the analysis, therefore, is to view the range of institutional alternatives that might be incorporated into intervention schemes, which will then be ultimately tested for feasibility and acceptability in a number of irrigated areas representing a spectrum of irrigation return flow control problems. More than anything else, the central concern has to do with the presentation of specific steps involved in the process of building a basis for implementation and for the adoption of desired changes.

The Research Approach

In general, the study undertaken by the interdisciplinary team has attempted to further the public and political decision-making process involved in policies, law, standards, and regulations for pollution control from agricultural uses of water resources. In outlining the thrust of such an approach, the following interrelated objectives have been identified as necessary:

a. the identification of appropriate technologies and the institutional alternatives that together may improve irrigation return flow quality control;

b. the assessment of combinations of technologies and institutions as to their feasibility of implementation in selected areas in the West, through field responses and community feedback;

c. the analysis of the process of change and decision-making as a basis for eventual efforts of implementing return flow quality control;

d. the consideration of trade-offs between engineering, economic, legal, and sociological alternatives within the context of larger established policies and goals.

In the proposed approach, there are five interlocking steps, in a process of cumulatively building experience with the problem and of providing an analytical framework for evaluating institutional alternatives.

1. The investigation of those current technologies which could control quality of irrigation return flow and the assessment of their impact on the problem.
2. The generation of alternatives, or identification and analysis of various

technical and institutional solutions to problems of quality control.

3. The assessment of those alternatives and a critical analysis of total system effects and of criteria for weighing alternatives.
4. Evaluation through the help of affected recipients and a juxtaposition of feasible strategies and programs of quality control.
5. The building of the basis for implementation with special emphasis on the factors that hinder or facilitate the adoption of new measures.

By using this type of an approach and through continuous interaction among members of the research team, a consensus as to critical findings has been established. The concern throughout the conduct of the study has been to provide concrete validation of the theoretical processes described above, and, at the same time, through interaction both within the team as well as with water users in the particular areas of concern, relate to actual circumstances the critical findings concerning solutions, constraints to implementation, and the basis for developing strategies for controlling irrigation return flow.

The problem does not reside exclusively on the determination of an "appropriate solution," although the last has been a central point in finding out what really can be done to communicate effectively the spirit of the law with regard to problematic situations in a variety of cases in the western United States. The concern begins with the process of *arriving at* appropriate solutions, in assessing in an interdisciplinary manner alternatives, and in outlining the steps for an eventual process of implementation of whatever is the agreed-upon "solution" or program.

However, it is important to underscore again the centrality of the search for an "appropriate" or "balanced" solution. A key element and assumption of the study has been that such a desired "appropriate" solution can be reached by considering through an interdisciplinary analysis a variety of factors that bring together what is technically sound, economically viable, legally pertinent, socially acceptable, and, finally, what is politically feasible or implementable. This search for the combination of a wide spectrum of conditions leading to the "appropriate solution" is articulated in the categories of Table 1.

In order to both further explicate this approach and, at the same time, summarize the central argument of our study, the key dimensions shown in Figure 1 may be used, where the sequence of the approach involves:

a. setting the stage, bounding the problem and considering potential solutions;

b. arriving at appropriate solutions and determining alternative strategies; and

TABLE 1

Key Characteristics of an Appropriate Solution.

APPROPRIATE SOLUTION

Technically sound	Technologically practicable
	Long-term benefits vs. short-term gains
	Ecologically non-damaging
Economically viable	Economically achievable
	Providing efficient resource allocation
	Promoting equitable distribution
Legally pertinent	Protects vested rights (due process)
	Complies with legal criteria in substantive law
	Complies with administrative procedures
	Promotes beneficial use concept
	Is characterized by flexibility & predictability
Socially acceptable	Congruent with current practices
	Consistent within cultural context
	Compatible with organizational structure
	Corresponding with desires of people
Politically feasible	Compatibility of interests (local, regional, national)
	Establishes priority of problems
	Compares severity, intensity and magnitude of potential effects
	Aims at constituency satisfaction

c. building the basis for implementation and facilitating the acceptance of appropriate solutions.

Figure 1 outlines also particular aspects or dimensions in each of the above phases. Each of these subdimensions has been intensively analyzed as part of the desired interdisciplinary synthesis aimed at building the basis for implementing a given solution (or, for relating *appropriate* to *acceptable* "solutions"). In addition, Figure 1 underscores the iterative steps involved in such a process. Thus, in implementing an appropriate solution (in making it acceptable) monitoring and feedback may allow the problems to be *redefined* (reexamine the stage, critical variables, law, or affected parties); the appropriateness of the solution to be *questioned* (especially with regard to trade-offs and local sensitivity); and the acceptability of the proposed solution to be *reexamined* in terms of the degree of local involvement, availability of implementation mechanisms and coordination between all responsible agencies.

In summary, the process of implementation brings together the objectives of the law and the desires of the recipients in a compatible, complimentary and negotiated scheme whose ultimate aim is the proper solution of problems of pollution and irrigation return flow.

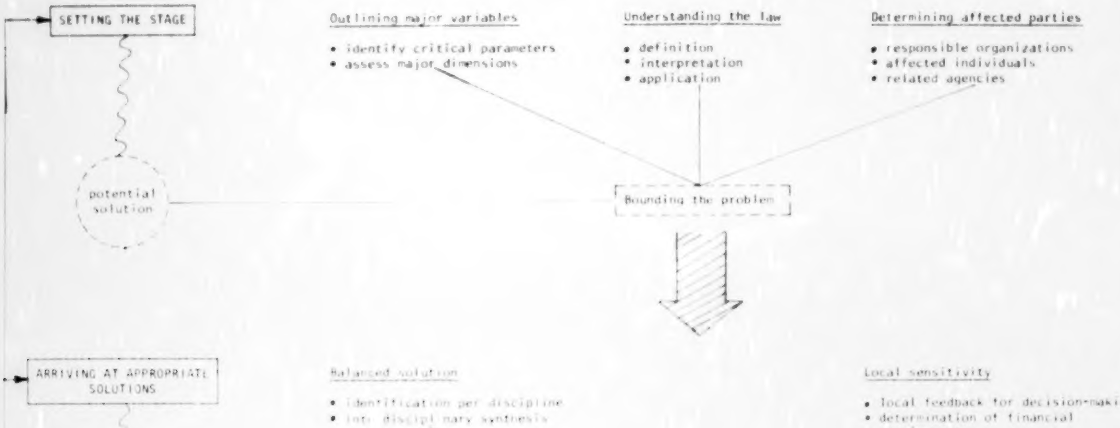
SETTING THE STAGE
Outlining major variables
• identify critical parameters
• assess major dimensions
Understanding the law
• definition
• interpretation
• application
Determining affected parties
• responsible organizations
• affected individuals
• related agencies
potential solution
Bounding the problem
ARRIVING AT APPROPRIATE SOLUTIONS
Balanced solution
• identification per discipline
• interdisciplinary synthesis
Local sensitivity
• local feedback for decision-making
• determination of financial requirements
appropriate solution
Determining alternative strategies
BUILDING THE BASIS FOR IMPLEMENTATION
Local involvement
• information and education
• local mobilization
• individual acceptance
Use of existing mechanisms
• reorganize existing institutions (enforce conditions of use)
• utilize existing organizations
Linkages between responsible agencies
• determine authority, control and span of responsibility
• approval by the state as to meeting requirements
• promotion of cooperation and combination of resources
• reestablishment of credibility between state and federal agencies and water users
acceptable solution
Establishing the process of implementation
Monitoring and feedback

Figure 1. A Sequential Paradigm for Building the Basis for Implementation

The essence of the approach developed is that the problem requires consideration of a number of alternatives leading to some solution. The process of implementation brings together problems and solutions, as well as an assessment of the various alternative strategies. This process is based on a juxtaposition of a set of assumptions and of related programs as outlined in the following manner:

Assumptions	*Examples of Intervention*	*Program*
-Improved Agricultural Practices	•Incentives •Market mechanisms •Legal enforcement •Centralized demands •Etc.	-Best Agricultural Practices
+		+
-Improved Water Management		-Best Management Practices
+		+
-Public Acceptability		-Public Mobilization

The key problem in this study was not so much the repetition of the conditions in the areas of concern that may hamper or facilitate potential change and implementation of new technologies (although this is a necessary part of the problem); but, the focusing upon very specific strategies and tactics required for a dynamic process of effecting change. The important aspect is to develop a paradigm as to how specific features of an implementation process can be outlined and, at the same time, formulate a particular plan for improving irrigation return flow quality in areas of concern.

Nature of the Problem

The following discussion deals with the parameters of the irrigation return flow quality problem. That is, it seeks to identify the particular causes of the problem in order to establish a basis for identifying potential solutions.

Much of the focus in irrigated agriculture has been to improve existing irrigation systems by increasing the water supply, rather than improving the use of existing water supplies to more effectively produce crops and reduce the quantity of return flows. Farmers generally perceive the solutions to water problems as revolving around more water supply; indeed, many of the existing institutional mechanisms for assisting irrigated areas facilitate this approach. As a consequence, many irrigated areas are over-irrigated which results in large quantities of irrigation return flows. In addition, in many cases these return flows result in significant water quality degradation. In such cases, there is a direct relation between the inefficient use of water and the resulting water pollution. Therefore, alleviating water quality degradation from irrigated agriculture will, in most cases, require increasing the efficiency of water use, which involves improving water management practices.

In improving water management practices, there exist a number of institutionalized constraints which make the actual acceptance of proposed practices difficult. Such practices require that irrigation return flow quality control include both dimensions of the resource problem — water quantity and water quality. Separate categories of laws have evolved for each dimension, each taking on characteristics which contribute to the problem and compound efforts to improve the quality of return flows. Also, these practices must employ a program that would incorporate cooperation between organizational entities and the individual user, something which is not now present. It is these constraints that constitute a major part of the problem at hand.

Problems of irrigation return flow quality are compounded by the specific perceptions of individual farmers regarding pollution and the geographic significance of the problem. Farmers know that using irrigation water will cause some degradation, but the point at which it becomes significantly detrimental and who is responsible are a major source of contention. Thus, many farmers either do not perceive the consequences of their action or they believe that with the existing means of irrigating (which are the correct means), the level of pollution is natural and, therefore, acceptable. In addition, there is the lack of a broader perception involving the regional nature of the problem, since farmers are mainly concerned about their own property. The critical point is that a water user's perception of the farming situation and the problem of water quality in particular dictates how that person will accept any innovative technology to solve a given "problem."

The above discussion relates some of the difficulties in gaining popular support for the necessity to alleviate water quality degradation from irrigated agriculture. However, the heart of the matter and a major cause of the problem is the use of too much water; thus, a central constraint to improving water use efficiency in the West is the present system of water law administration. Water is allocated, distributed and administered under a body of law which grants to the user a water right synonymous to the property right interest one can acquire to land. The water right is not one of absolute ownership, but rather one for the use of water only and subject to specific conditions and concepts which theoretically are prescribed to protect the public and other users.

Until the past few decades, water used for irrigation was not considered a type of use that required strict application and enforcement of the law to achieve water quality goals. In fact, many of the concepts and conditions provided guidelines for allocation and distribution, with implementation carried out when the water right was granted and thereafter only when severe abuse occurred or another user complained.

The primary elements of the water quantity law which contribute to both the problem of degraded return flows and efforts to improve the quality are:

- Failure to enforce legal conditions for water use, namely beneficial use and non-waste.
- Constraints in the law which prevent the transfer of excess and saved water to other lands or users where it could more effectively be used.
- Lack of adequate recognition of the legal *duty* to include water quality control as an attribute of the water right to be enforced particularly by irrigation districts.
- Restrictions or deficiency in the law on the use of low-cost funding from state/federal programs for water quality control.

These four factors provide the explanation for water user conduct as well as constraints to adoption of more efficient physical and technical solutions that may not only improve the quality of return flows, but also increase crop production.

The doctrine of prior appropriation has led water users into a continual diversion of their full "water right" for fear of loss of this right if the full amount were not used. Therefore, users have been unwilling to sell, rent or lease any portion of their water right, which could have led to economic benefits to both parties, as well as more efficient use of the resource. Thus, there has been no market for reallocating irrigation water. In addition, farmers have been able to pass on to downstream water users part of the costs of production in the form of pollution.

The present institutional arrangement allocates water on the basis of a priority of rights rather than on the value of use. The price of water is generally the cost of its conveyance to the farm and does not represent the value of opportunities foregone. The result is that the use of water is not competitive; it is not allocated to its highest valued use; and its relatively low price causes it to be excessively applied.

With the exception of irrigation water, farm inputs are allocated through markets. Labor and capital, for example, are allocated and priced through markets according to the value of their use. Consequently, water tends to be relatively cheap, so that profit-maximizing farmers rationally substitute water for capital and labor (i.e., water management) in the production process. The result is an over-application of water with associated return flow pollution.

Irrigation return flow pollution also results from the avoidance by farmers of some costs of production. The profit-maximizing farmer attempts to minimize production costs. In so doing, however, he may select production methods and techniques which are low cost to him, but polluting to downstream water users. Alternative production methods and techniques may be less polluting but higher cost to the farmer. By selecting the lowest cost methods and techniques, the farmer passes on part of the costs of production to downstream water users in the form of water pollution.

Irrigated agriculture is a collective enterprise involving all of the users and improving existing water management practices, whether to alleviate water quality degradation or more effectively utilize existing water supplies to increase crop production, certainly requires collective action. There exist a number of organizational entities that administer irrigation, but, generally, there is a lack of explicit rules established for the management of this resource with regard to quality. There also exists a lack of communication and coordination between agencies and districts, and the farmers with regard to how the water should be managed.

As a consequence of the lack of an explicit institutional framework surrounding this problem and certain individual perceptions that do not enhance a specific water quality management ethos, implementing a program of irrigation return flow quality management can be expected to be a very difficult task, further complicated by the economic and legal conditions outlined above.

Identification of Potential Solutions

The range of possible solutions to irrigation return flow pollution is, of course, a function of the parameters of the problem identified in the previous section. Thus, potential solutions are discussed in this section in terms of the causes of the problem.

There are a number of potential solutions for controlling the quantity and quality of irrigation return flow. The irrigation system may be subdivided into the water delivery subsystem, the farm, and the water removal subsystem. The use of efficient practices in the delivery canals and pipelines, as well as improving on-farm water management, will minimize the problems in the water removal system. In most cases, the key to minimizing irrigation return flow quality problems is to improve water management practices on the croplands.

The water delivery system can be improved by lining canals and laterals, using closed conduits for water transportation, providing adequate control structures, and installing flow measuring devices.

Improved practices that can be used on the farm include judicious use and application, or placement, of fertilizers, use of slow-release fertilizers, controlling water deliveries across the farm, use of improved irrigation application methods (e.g., subsurface application, sprinkler irrigation, or trickle irrigation), control of soil evaporation, use of a pumpback system to allow recycling of surface return flows, erosion control practices (e.g., contour farming), and irrigation scheduling to insure that the proper amounts of water are applied at the times required by the plants.

In the water removal subsystem, open drains and tile drainage can be used to collect return flows, which can then be subjected to treatment on a large area or basin-wide basis, if necessary.

Identifying appropriate technological solutions must be related to the nature of the problem, i.e., water quality degradation as a result of surface return flows or subsurface return flows, or both. Knowing the sources of pollution, then potential solutions can be identified. The appropriateness of such solutions will be related to other "site specific" physical parameters, as well as historical irrigation methods and practices in the area, and the perception of the users regarding the necessity for change. In addition to informing the water users of the existing irrigation return flow problems, it becomes necessary to demonstrate appropriate technologies in order to gain farmer acceptance. This phase, as well as area-wide implementation, could easily be hampered by the lack of sufficient technological assistance and by the legal constraints on the use of low-cost government funding to achieve water quality improvements at the farm level.

Improved irrigation water management practices will almost invariably result in reduced demand for water diversions. The real difficulty in gaining water user acceptance lies in solving the problem of who benefits from the saved water.

At the present time, the irrigator cannot benefit from the water saved by improved irrigation water management practices. Consequently, little progress in water quality control of irrigation return flows can be expected until the water right issue is addressed.

One of the viable alternatives for producing a positive incentive for water users to benefit by improving their irrigation system is to establish a market for irrigation water. In order to minimize the disruption of the present institutional arrangement, the market form identified as having the most potential is a water rental market. The demand for rental water would represent its addition to the total value of output per additional unit of water. The market supply schedule would represent the water right holder's increasing opportunity cost of using the water himself rather than renting it. The market equilibrium price would be greater than the current costs of conveyance. Those demanding and supplying would have an economic incentive to use water more efficiently. That is, a rental market would increase the price of water to its marginal value in production and would, thus, encourage more use of labor and capital (i.e., water management) in combination with the water, thus reducing return flow pollution.

Such an arrangement would take as given the present structure of water rights and allotments. Those with water rights or allotments, however, would be allowed to rent surplus water to other users without jeopardizing their rights or allotments in the future. In most states, such a market could be created by removing the legal and physical uncertainties associated with such transfers under the present system. Transfers within irrigation districts of excess or saved waters requires changes in both federal reclamation and some state laws.

A market allocation, however, might not be sufficient to correct all return flow pollution. Farmers would still have a profit motive for externalizing all possible production costs, including the costs of controlling pollution. Waters users (or irrigation districts and companies) should be required to internalize costs imposed on other water users, public or private, through adoption of standards and criteria for beneficial use and creation of programs (voluntary incentives) and penalties (compulsory compliance) that could be employed by water administrators to protect adversely affected parties. In economic terms, this means the imposition of taxes and subsidies. The particular form and application of such taxes and subsidies can only be specified for particular cases. In general, however, taxes can be utilized to adjust the price of water to approximate a market price, thus inducing farmers to be more efficient in its use. Taxes can also be used to penalize farmers for return flow pollution, but monitoring costs are typically prohibitive. Generally, subsidies in the form of direct payments or technical assistance and capital improvements appear most applicable for improving on-farm management of water. Finally, taxes and subsidies may be jointly applied as, for example, with a tax on water to approximate its market value and the revenues from this tax being used to subsidize farmers to adopt less polluting methods and techniques of water use.

The argument made above concerning legal considerations involved in problems of water quality has set the stage for potential solutions improving the law's sensitivity and ability to address such problems. Essentially, identifiable solutions include: adoption and enforcement of criteria for beneficial use, waste and water duty; removal of constraints concerning transfer of excess or saved waters within irrigation districts; promotion of low-cost funding; internalization of costs through adoption of standards for water use, creation of programs, or compulsory compliance, all of which could be employed by water administrators to protect adversely affected parties.

Finally, the various alternatives must take into consideration both individual attitudes and the organizational structure that provides the rules and mechanisms which influence individual behavior. For the individual, potential solutions must involve an awareness of the critical character of irrigation return flow. On the other hand, for the organizational context, solutions revolve around the creation of mechanisms and practices which can facilitate the adoption of means for acceptable water quality standards.

Awareness by the farmer entails two conditions. First, the awareness should be towards specific on-farm management procedures which enhance water quality. In addition, a holistic approach as to why improved water quality will enhance not only his neighbor's operation, but also his own, must be explicated. Clean water should be seen as beneficial to the farmer and this benefit must be viewed as one that can be attained only through an area-wide involvement of water users.

Instilling this individual behavior as a public good can only be accomplished when the organizational structure supporting the farmer embraces broader and firm commitment to cleaner water. This can be done by using the existing structure; by changing or restructuring present arrangements; or by adding to the existing framework. The use of existing mechanisms such as the extension service, SCS, the local mass media, Co-ops, etc., can provide communication and information networks from which the individual farmer can become aware of the problem and the solution. Yet, some valleys do not have a well-organized system of communication by which water quality conditions are adequately processed, investigated, and disseminated. Such an organization can be established either by modifying the existing structure or creating a new one altogether. This organization should work with farmers, agencies and the public in such a manner that it serves as a focal point for water quality information; and as a nodal point through which flow and exchange of information from above and from below can be transferred into coherent, collectively arrived at policies.

It should be noted that in the juxtaposition of individual and organizational approaches, the assumption was made that acceptance of new management procedures will follow dissemination of knowledge and awareness. However, this is not always the case. Since there is not a necessary or sufficient causal relationship between "appropriate" and "acceptable" solutions, systems of rewards and penalties must also be established in order to provide support, to reinforce desired behavior, and, generally, in order to make sure that proposed solutions will not die because of neglect or lack of sustained implementation by the users.

Yet, as with all other solutions, these proposed monitoring and enforcement mechanisms must have an effective say or part in any decision-making process regarding irrigation return flow quality control. For, at the end, the pursuing of an effective water policy is part of a larger commitment and of an ethos that combines individual motivation and economic opportunities within an organizational context that makes possible collective social action and timely technical interventions.

Generally, the alternative solutions proposed for evaluation ranged from those which were wholly technical (e.g., rehabilitation of distributive systems) to those which were institutional (e.g., creation of water markets). Some were combinations of technical and institutional measures which would cause improvements in quality of return flows (e.g., cost sharing arrangements for improved irrigation facilities). They can be generally classed as: 1) those directed to sources of water, generally, those which would increase supply; 2) those concerned with the influent, i.e., the water diverted to agriculture; 3) those associated with the management of land and water on farms; and 4) those which were concerned with the effluent, i.e., the return flow.

Testing the Implementability of Potential Solutions

Following the identification of potential solutions for return flow quality problems, the team directed its efforts to evaluation. It was understood that alternative solutions would be more or less acceptable (and thus implementable) depending on their impacts on the affected parties. Testing procedures were devised to determine technical, economic, political, and social acceptability of alternative solutions. They involved: 1) the project team; 2) state and federal agency personnel; 3) irrigation water managers; and 4) water users.

The first evaluation was done by the project team. Composed as it was of engineers, economists, sociologists, and an attorney, the team was able to judge alternative solutions in terms of technical, economic, legal, and social feasibility (per criteria outlined in Table 1). Obviously, inappropriate and ill-advised solutions were weeded out, though the number was not great. Alternatives with potential for significant impacts on the quality problem and those without prohibitive costs were retained for evaluation by others. The team wished to present the widest possible range of alternatives to succeeding evaluators.

A second evaluation was accomplished by federal and state agency personnel, chiefly those presently or prospectively involved in administration of quality improvement programs. The alternative solutions were thus screened by those with technical and legal expertise, a group with a special concern for administration of laws and programs. This group tended to sort out those solutions which did not fit within the framework of existing laws, rules and regulations and which would therefore be difficult to implement. The list of alternatives was reduced, but not so as to exclude some solutions which would be possible with changes in laws, rules and regulations.

The third evaluation was completed by managers of water supply agencies (e.g., irrigation companies and districts) and their boards of directors. These were individuals having responsibility for distribution of water among farms of members and patrons and for maintenance of system facilities. Because they are potentially responsible for administration of revised rules governing diversions and use of water, they tended to resist measures of control. But they were aware of water quality problems; they were generally convinced of possibilities for improved use of water; and they tended to favor quality control measures located and administered at their level rather than at higher or lower levels.

Finally, the fourth evaluation was done by the farmers who use water in irrigation of crops. They were interviewed separately; there was discussion of the return flow quality problem; and potentially useful solutions were outlined and discussed. These individuals, though alarmed by present efforts to control their use of water, showed both ability and willingness to comprehend problems of water quality and deal with them. They were very practical in their judgments of implementability of the various alternative solutions, and they tended to favor those measures aimed at improved use of water in agriculture. It was these measures over which they had some control.

The overall response to all such solutions depended somewhat on who was doing the evaluating. Administrators were more inclined to favor the technical solutions which were most familiar to the agency personnel. They were inclined to prefer measures that they could control and administer, since their experience was largely with water development and water treatment. Users tended to prefer those solutions which emphasized management of water in agriculture. They were aware of some inefficiencies in water use, some non-conservative uses of water and land, and they knew of possibilities for improved management. Managers of distribution systems were aware of inadequacies in their systems and liked proposals for improvement. They tended to favor the influent control measures, i.e., solutions affecting diversion and allocation of water among users. Farmers understood these solutions, too, but were understandably concerned about possible reductions in their annual allotments.

Probably the greatest support was found for those solutions that dealt with improved management of water in agriculture. There was appreciation in most of the project areas for the efficacy of those measures that affected on-farm use. But there was also appreciation for solutions proposing new controls on diversions and use, for in two of the project areas water allocations are usually large, i.e., there is an abundant supply. The managers of distribution systems and farmer-users of water know that greater efficiencies in water use can be achieved. Their concern is for loss of rights which have been long held and carefully guarded. There was some interest in water markets, as means for reallocating supplies, but unfamiliarity with such a measure in some areas prevented enthusiastic support.

CONCLUSIONS

The control of water quality raises two basic issues (which are also present in any water resources management scheme), namely, incentives and enforcement. Questions here include: What organizational structure is going to make the rules and regulations and also enforce them? How is the present problem of insufficient control going to be alleviated? How can the marginal value of excess water be operationalized to a water market? What is the situation with regard to intra-system, interstate and inter-basin transfers of water? Broad as these questions may be, they are also part of the general considerations necessary for the eventual control of irrigation return flow.

As repeatedly stated, three basic dimensions of the irrigation system are central in all strategies of return flow control: water delivery, the user and removal efforts. With regard to delivery, the critical point is that of control at the inlet. It has been early agreed that the thrust of the various alternatives should focus on the user. Improvements in delivery systems, use of better technology, improvements in removal, etc., should all be built around the user. The critical point of this dimension is the manner of applying the water on the land, i.e., on-farm water management. Constraints to better on-farm management include such factors as lack of information/technical assistance, lack of control over the water, existing water rights, lack of physical facilities for use of water, and the lack of institutional facilitators (tradition, value system, education, etc.). Simply, the problem is one of motivating users to internalize better management techniques.

Recognizing the thrust of the present study in outlining the process for identifying, evaluating and building the basis for implementation, the following conclusions summarize the central findings:

1. The roots of the problem are the institutional arrangement for allocating water, i.e., legal rather than market adjustment.
2. The most appropriate solutions deal with the diversions and use of water rather than treatment of irrigation return flows, i.e., the cause rather than the symptom of the problem.

3. Solutions mutually beneficial to both water quality and the farmer are most implementable, such as:
    a. subsidies for on-farm physical improvements;
    b. providing technical assistance;
    c. water rental markets.
4. Various means of improving on-farm practices remain a useful approach for controlling irrigation return flow.
5. Irrigation districts play a major role as part of existing organizations in implementing solutions.
6. Informational and educational programs to assist individual farm operators must be instituted early; be imaginatively conceived; and be continuously monitored, modified and upgraded if motivation for change is to be encouraged.
7. There must be a clear definition as to who has authority, control and responsibility for specific tasks associated with return flow control.
8. Major technological breakthroughs should not be relied upon for providing return flow control; instead, emphasis should be on a combination of current technologies and of institutional measures.
9. State-wide and regional advisory committees should be part of a continuous effort for cooperation, coordination and combination of efforts and resources.
10. Structural opportunities for improvements should be utilized with sensitivity to local conditions and through local mobilization as part of a slow, iterative and long-range process of implementation.
11. Credibility and trustworthiness of federal and state agencies in the eyes of water users provide the important final ingredient in understanding the need for change; in motivating individuals for accepting appropriate solutions; and, in creating a climate of cooperation and credence as to the need and ultimate usefulness of a larger social policy concerning "cleaner water."

In summary, the final approach to irrigation return flow quality management requires an imaginative combination of physical methods, implementation measures and institutional arrangements. The success of such a synthesis will be ultimately based on a gradual, if not hierarchical, testing of alternative solution packages, on sensitivity to local conditions, and on a committed, open process of communication linking appropriate authorities with individual users.

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